DYNAMIC MODELING AND EVALUATION OF RECURRING INFRASTRUCTURE MAINTENANCE BUDGET DETERMINATION METHODS

THESIS

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Abstract

The focus of this research is using system dynamics modeling to evaluate the impact of missed scheduled maintenance due to budgetary constraints. Missed maintenance cannot be made up and the benefit to the facility's serviceability is lost. The cumulative effect on an entire facility's life span is that it is unable to reach its designed life expectancy. Replacement construction costs are hundreds, thousands, or millions times more than the annual maintenance repair costs. Therefore, Air Force civil engineers must be capable of evaluating maintenance strategies in a dynamic environment to determine the budget strategy's prolonged effect on infrastructure serviceable life. The results of the evaluation demonstrate how five major categories of infrastructure maintenance budgets change infrastructure's serviceable life. The modeling process provides considerable insight into these budget methods that must be considered to determine what is best for the infrastructures serviceable life.

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Matthew P. Jefson

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DYNAMIC MODELING AND EVALUATION OF RECURRING INFRASTRUCTURE MAINTENANCE BUDGET DETERMINATION METHODS

I. Introduction

Background

Base infrastructure and facilities are an integral part of every Air Force installation; they provide the platform, from which the Air Force trains, equips, deploys, and fights. From this perspective, facilities and infrastructure are defined as "… all existing buildings and other base utilities and pavements used to support the existing mission and normal growth of the base" (Air Force Pamphlet 32-1004, 2004). It is important to recognize that the phrase "normal growth" implies a system that must adapt to the changing environment and cannot be frozen in time. Although facilities and infrastructure are continuously degrading, they must remain at a serviceable level to meet the mission requirements of the Air Force.

The Air Force tracks infrastructure readiness through Infrastructure Readiness Reports (IRR). This report shows the commander's assessment of how well the base infrastructure meets the mission requirements. It is a tool that measures the ratio of programmed project dollars against the overall replacement value of the infrastructure. In other words, it is a tool that uses a constructed proxy measurement to assess base condition. However, this assessment may or may not represent the serviceability of the base's infrastructure since it focuses on replacing infrastructure rather than maintaining it. Furthermore, the tool provides no indication of how well the base is managing the aging process of its facilities. Yet the Air Force uses this tool to make decisions regarding base infrastructure maintenance and renewal funding.

Without a proper emphasis on maintenance, a base's civil engineering recurring maintenance program will not be effective at preserving the serviceability and longevity of the infrastructure. Budgeting to prevent degradation is extremely difficult and the budget must be closely evaluated. To help adequately assess and develop infrastructure maintenance budgets, a dynamic evaluation strategy capable of looking at an entire system of interactions is necessary. This research effort tackles that dynamic evaluation by examining various budgeting methods and how they interact with the infrastructure serviceability.

The serviceability of a facility is the measure of the capability of the item to meet its mission requirement. Note the concern here is not designed purpose, but rather the mission requirement. Many older facilities have seen the activity housed in them change dramatically throughout the years and no longer function as originally designed; however, the facility still plays a vital role in meeting the installation's mission requirement. Therefore the serviceability is a paramount concern when looking at facilities and infrastructure.

Infrastructure, from the time of initial construction until final demolition, is in a state of degradation eroding the facility's serviceability. Some of the contributing factors to the magnitude of the degradation are climate, use, abuse, neglect, mission changes, and technological advancement. Degradation may be invisible to the facility user and maintainer until it manifests itself in failures and breakdowns. Inoperable heat or air conditioning systems, broken doors and windows, leaking roofs, and holes in the walls are very notable failures that bring facility degradation to the user's attention. Proper preventative maintenance actions can lessen the impact of this degradation and prolong the serviceable life span of the facility.

Often preventive maintenance is cyclical in nature and must be performed on a schedule. Therefore, preventive maintenance is often called recurring maintenance. Preventive maintenance is extremely important to the infrastructure or facility's longevity. Consider the example of a vehicle. The value of an engine oil change, tire rotation, and chassis lube is directly connected to the life expectancy of a vehicle and is not questioned. Likewise, infrastructure and facilities have well known recurring maintenance activities. They include tasks such as greasing mechanical systems, sealing windows and doors, and tightening of electrical connections. These scheduled yearly, quarterly, monthly, or weekly actions can often seem meaningless and unimportant to the casual observer in terms of the serviceability of the overall facility. These preventive actions are often overshadowed by other competing priorities that utilize the funding or man hours required for their completion. If a preventive maintenance item is missed it cannot be made up by completing the action twice in the next week, month, or year. The benefit of the preventive maintenance is lost, and the degradation goes unchecked dropping the serviceability of the facility.

But what was the value lost with regard to the overall facility or infrastructure system serviceability? Ultimately, the facility's life span is shortened since the facility's serviceability no longer meets mission requirements. For example, the value of an unexercised valve is only realized when a water main leak is unable to be isolated, and a pump that has not received its proper preventive maintenance is only a concern when there is no longer heat in the facility. While these failures have fixed repair costs, what was the impact or loss of serviceability to the entire system or facility? The loss of serviceability leads to a shortened life span for the facility and the replacement date was just moved forward.

Modern construction practices drive replacement costs hundreds, thousands, or millions of times more than the repair cost or the missed routine maintenance costs. This high increase in replacement cost led General Michael E. Ryan to say in the Air Force Magazine (December 2000), "…we are on a 250-year replacement cycle for our infrastructure, where our people work and live." The job for the Air Force civil engineer is to development a facility/infrastructure maintenance budgetary strategy that will prolong the life of the infrastructure enabling the Air Force to continue meeting its mission objectives.

Budgetary decisions for preventive maintenance are complex and involve several interrelated influences, which can be called a system. In order to evaluate budgetary strategies, the entire system from budget constraints, preventive maintenance, infrastructure and facility degradation, to the feedback loops that create the maintenance budget, must all be evaluated simultaneously. If you evaluate the individual components of the system false results could result. Therefore, to evaluate the infrastructure maintenance budgetary system, one must look at the entire system in a dynamic environment.

Research Question

The main objective of this research is to more accurately prescribe and evaluate facility/infrastructure preventive and recurring maintenance policy that will extend the serviceable life while complying with Air Force budgetary constraints. To answer this question this research will be guided by the following investigative questions.

Investigative Questions

1. What models for facility/infrastructure maintenance budgeting exist?
2. What are the feedback loops that influence infrastructure maintenance?
3. What is/are the typical lifecycle serviceability behavior patterns for base infrastructure and facilities?
4. What are the controllable influences on the lifecycle serviceability behavior patterns?
5. What is the existing Air Force policy on the controllable influences?
6. Is the policy preserving the Infrastructure for mission objective sustainment?
7. Can a facility-specific dynamic method be developed that substantially improves serviceability of Air Force facilities and infrastructure giving a more accurate picture of the cost of incomplete preventive maintenance?

Proposed Methodology

1. Conduct a literature review on current AF and public facility and infrastructure recurring maintenance programs, condition assessment programs, and life cycle cost analyses to identify a frame work for construction of an evaluation metric.

2. Use the system dynamics paradigm of logic to construct a model to evaluate the achievable long-term impacts of varying maintenance management policies.

3. Evaluate the different methodologies of maintenance practices to formulate optimum recurring maintenance budgetary policies using the constructed model.

Limitations

Serviceability of a facility or infrastructure system is a subjective measure. It is therefore not easily defined or measured. The impact of loss of serviceability is evident but is also difficult to quantify. Therefore these two measures are very soft variables that, using system dynamics, can be evaluated in time but cannot make specific inferences about their quantifiable amount. The effort will be limited to exploring more optimum behavior patterns for serviceability that will lead to longer serviceable life.

II. Literature Review of Facility Infrastructure Maintenance and Repair Budget Estimation Modeling

Infrastructure facilities generally have long service lives, typically between 30 and 70 years. This life span figure is used by designers and planners for cost-benefit and other calculations with little to no regard for the required serviceability. Seldom is any meaningful calculation of life-cycle analysis accomplished, and these figures result more from so-called standard practice than from design initiatives (Lemer, 1996).

Measuring a facility's or infrastructure's performance over its service life is paramount. The measure of a facility's performance is generally measured in dimensions of effectiveness, reliability, and cost (Lemer, 1996). Lemer defines effectiveness as the degree to which the infrastructure meets the demands or requirements of the owners, users, and neighbors. Accurate measurement of this effectiveness in economic or financial terms is extremely difficult due to the lack of a direct link between the owner's, user's, and neighbor's satisfaction and the remaining serviceability of the infrastructure and facility. Reliability is defined as the probability that the serviceability of a given facility or infrastructure item will be sustained throughout the entire design lifetime. Reliability is extremely dependent on the preventive maintenance performed. The preventive maintenance in-turn drives the cost measurement. Cost, often referred to as 'life-cycle cost' encompasses the resources necessary to plan, design, construct, operate, maintain, and convert the facility to a new use or demolish the facility (Lemer, 1996). Individual owners, users, and neighbors establish a comprehensive set of measurements for effectiveness, reliability, and cost that are acceptable to them. This metric set can be translated into a minimum acceptable performance level. Lemer graphically represented performance over time as shown in Figure 1.

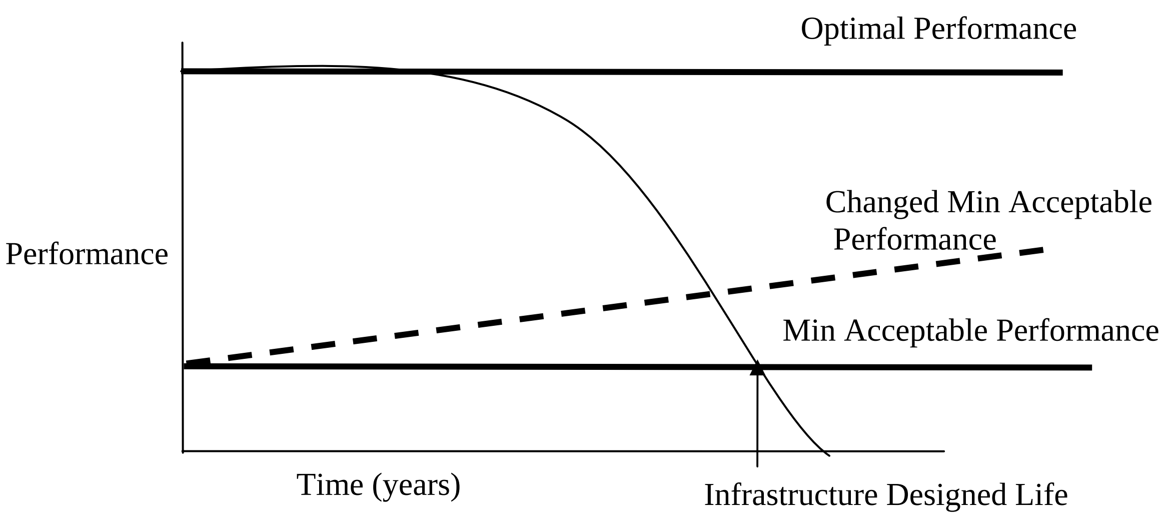

Figure 1 Lemer Performance Behavioral Pattern

In the figure above, Lemer shows that the performance of a building holds relatively constant over a large part of its lifespan and then sharply drops in the latter stages of its life. Lemer makes the assumption that during an infrastructure's lifecycle, the performance remains at a high level for years barring a catastrophic failure. Lemer also assumes proper maintenance occurs and use levels are at designed loads. This initial phase is followed by a period of decline due to wear and aging that eventually and inevitably overtake maintenance. The declining performance is most notable to maintenance personnel at first and users second. The users often find work a rounds or alter their work or behavioral patterns to compensate for the decline. As the deterioration of the facility or infrastructure continues, eventually the minimum acceptable level is reached. However, this is not the end of the facility's life. The final renovation, replacement, or retirement decision for a facility by the owner is a political decision that involves a wealth of debate as to whether the condition of the facility or infrastructure is truly unacceptable and to what degree (Lemer, 1996).

In Figure 1, Lemer also demonstrates a possible change to the minimum acceptable serviceability. Lemer accounts for this change with four factors. The first is technological changes that dictate larger dimensions or make systems obsolete. The second factor is regulatory changes that impose new requirements, thereby causing the facility or infrastructure to need a renovation or modification. The third element Lemer discusses is economic or social changes. These are more subjective in nature and more difficult to define. The best example is a farmer's coop may no longer be needed in a suburban neighborhood now surrounding it due to urban sprawl. The last factor Lemer accounts for is the behavioral change of the user and or owner of the facility. Behavioral change means the user finds another preferable infrastructure. This changes the infrastructure's minimum acceptable level. As an example, Lemer suggests the removal of a rail spur because of the shift in American culture preferring individual automobiles to public rail travel (Lemer, 1996). These factors can work independently or all work together to change the minimum acceptable serviceability requirement.

The key for users, owners and maintainers is ensuring the facility achieves the designed life-span. In order to do this, infrastructure maintenance must be accomplished. In many cases, the operation to fix or repair the damaged infrastructure is very costly. As a result, facility and infrastructure maintainers attempt to preempt these failures through preventive maintenance.   The concept of preventive maintenance is not new. Its roots date well back into the nineteen hundreds with the advent of the industrial age. Machines, used in place of large labor parties, introduced the need to maintain the machinery such that it would not undergo failure, and the idea quickly spread to facilities and infrastructure. Today, the need for cyclic facility maintenance is well recognized. Sharp in his 2002 thesis stated,

> "companies that methodically identified their requirements and used those requirements as the basis for allocating funds to meet those requirements incurred the least impact from facility problems on their daily operations." In comparison, companies that allocated funds based on methods other than maintenance and repair (M&R) requirements typically under-funded those requirements, resulting in facilities that did not meet their needs."

Sharp (2002) conducted a case study of the top executives from several Fortune 500 companies, most notably the Chrysler Company. He concluded that successful companies recognize the need for preventive maintenance. Organizations desiring continued success and mission sustainment must recognize preventive maintenance is needed and must not neglect their high investment of capital in infrastructure and facilities.

The Department of Defense (DoD) is the largest public facilities and infrastructure owner in the United States, holding the deeds to approximately 80% of all public facilities and infrastructure (Ottoman, 1999). The DoD fully utilizes its facilities and infrastructure for training, housing, and deploying military forces to promote the security of the nation. As a result, the DoD commitment to the care and upkeep of its facilities is resolute. The Air Force, as a DoD member, shares this commitment. The Air Force has an established method to identify and fund Maintenance and Repair (M&R) requirements. The Air Force's method takes inputs from infrastructure users and maintenance staffs to identify infrastructure shortfalls and mission impacts resulting from degradation. As the mission impacts escalate they transform from mission impacts to mission failures, the issues are escalated to the engineering design staff, which is primarily charged with identifying, programming, designing, and construction of replacement needs.

The Air Force's budgetary support for facilities and infrastructure comes from two major sources of funding. The first is Operations and Maintenance (O&M) funds. These funds are for preventive maintenance and repairs. O&M funding levels are based on a percentage of the plant replacement value (PRV) of the base's facilities and infrastructure (DoD, 1989). The second major source of facility and infrastructure funding is Military Construction (MILCON) dollars. MILCON funding is appropriated for specific replacement projects identified by the installation through programming documentation that is reported to Congress. O&M and MILCON funding provide installations the means to maintain, replace, and grow their facilities and infrastructure to meet the installation's mission requirements. Appropriations for the military are under constant scrutiny and must be well defended. Infrastructure and facility O&M and MILCON funding is not limitless. It is constrained by Congressional appropriations and authorizations.

The Air Force title for O&M is Real Property Maintenance Activities (RMPA) (Robinson, 2004). These activities include demolition, real property services (RPS), and Sustainment, Restoration, and Modernization (SRM) (Robison, 2004). Demolition is the disposal of excess or no longer serviceable facilities and infrastructure while RPS includes utility bills and service contracts (Robison, 2004). Lastly is the SRM funding, which includes maintenance, repair, and construction of facilities and infrastructure done by in-house forces and contractor forces. The hierarchical structure of this funding is shown in Figure 2.

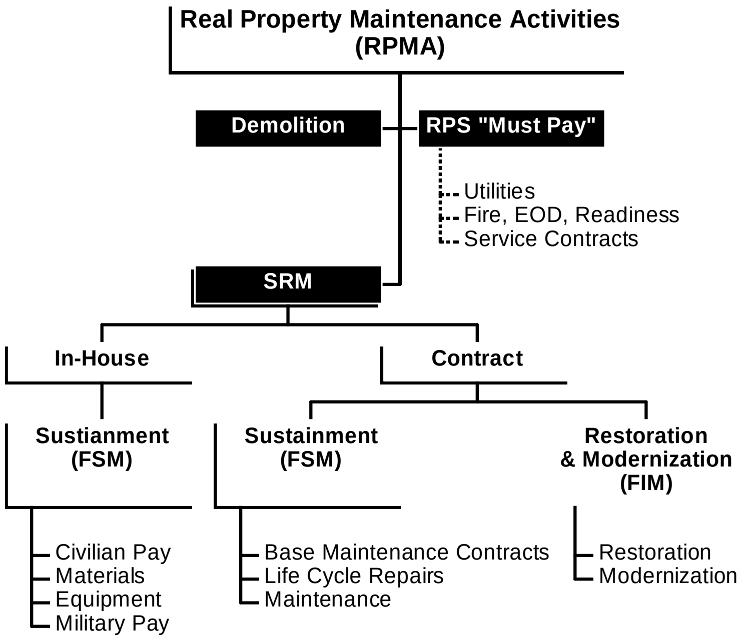

Figure 2 Air Force Funding Hierarchical Structure (Robinson, 2004)

Looking further into the SRM portion of the hierarchy, sustainment (FSM) is defined as annual maintenance and scheduled repair activities necessary to maintain the inventory of real property assets through its expected service life. The other half of the SRM hierarchy is the Restoration and Modernization (FIM) portion (Robinson, 2004). Restoration is defined as the repair and replacement work to restore facilities damaged by inadequate sustainment, excessive age, natural disaster, fire, accident, or other causes (Robinson, 2004). The Modernization part includes alterations of facilities solely to implement new or higher standards, regulatory changes, accommodation of new activities, or to replace building components that typically have a life expectancy greater than 50 years (i.e., foundations and structural members) (Robison, 2004). Included in restoration and modernization funding are alterations necessary to meet the demands of a new mission bed-down (Robison, 2004). This terminology defines the vocabulary used by the Air Force in consideration of facility and infrastructure maintenance funding.

The methods used in the facility and infrastructure maintenance industry are as diverse as the institutions and companies that use them. Each has it own way of determining how much funding is to be placed into facility and infrastructure upkeep. The determination of how much funding is needed to complete these various activities is accomplished in one of four primary methods. The four primary recognized categories of M&R or O&M budgetary methods are PRV methods, formula-based methods, life-cycle-based methods, and condition assessment-based methods (Ottoman, 1999). These four methods are not mutually exclusive; most individual user-specific methods are a hybrid of two or more of these methods growing out of the needs of the individual user (Ottoman, 1999). For organization and classification, one can use these four major categorical headings to provide a label for organizing the various budget determination methods being used. The following is a more detailed discussion of each of the individual methods and the internal influences upon which each rely to determine the M&R maintenance budget requirements.

Plant Replacement Value (PRV) Methods

The current method of choice for the Air Force to determine O&M funding is to assign budgets by taking a percentage of the estimated replacement construction cost of the facilities or PRV. The PRV approach to M&R budgeting is a function of the actual construction costs for a replacement facility (Ottoman, 1999). To determine the M&R budget amount, one takes the replacement construction cost value and multiplies it by a given or assigned percentage. The amount is the budgetary figure for the plant's M&R. PRV's fundamental premise is that it is intuitive to maintenance personnel and upper levels of management that larger, more complex facilities and infrastructure take larger M&R budgets to maintain (Ottoman, 1999). PRV budgeting recognizes one can capture the complexity and size of a given infrastructure item by looking at the item's replacement construction cost, giving way to a model for budgeting for M&R. Different public and private institutions use different percentage functions to determine the value of the PRV percentage. Table 1 shows the comparison of five major categories of institutions and their respective percentage of PRV given to M&R.

Table 1 Annual Investment Levels as Percent of PRV (Barco, 1994)

Organization	New Construction (%)	Maintenance and Repair (%)	Total (%)
Department of Defense (DOD)	1.6	1.4	3.0
Public Works Infrastructure (waste disposal, transportation, and water)			4.5
Major Colleges and universities	6.9	1.5	8.4
Major Private corporations	5.4	3.5	8.9
Non-DOD government entities	8.2	1.4	9.6

Note: Constant FY87 dollars.

There are three key relationships that influence the PRV method: 1) the relationship between the construction replacement cost and the M&R budget, 2) the relationship between the decision making management and the percentage multiplier, and

3) the relationship between the complexity of a facility and its construction costs. These relationships and influences define the PRV method.

The PRV method is not without blemish, however. One relationship not found in the PRV method is the tie between the cost of the maintenance activities and the budget. Whether this shortfall is just a perception or a factually based argument it is not well discussed. But proponents of other budgeting methods definitely point out the lack of linkage between the actual tasks to be completed and the determined budget needs.

Formula-Based Methods

A formula-based method uses a mathematical expression made up of easily quantifiable variables. The variables serve as descriptors of the base's facilities and infrastructure serviceability condition, construction type, age, and other salient characteristics. The results of the formula produce an estimation for the annual budgetary M&R requirements. The expressions range from simple single-variable equations to very complex algorithms (Ottoman, 1999). The level of complexity is user dependent. Most formula-based methods include the use of cost factors for the facility's given location (Ottoman, 1999). The formulas are not for dictating how much to spend on any one building in any one year but rather are designed to estimate the M&R budget need for an entire facility system or a group of buildings (Sherman-Dergis, 1981).

In the Dergis-Sherman Formula method, the annual budget appropriation is a combination of two distinctly different sets of factors. Those relating to the building, facility, or infrastructure and those relating to the political arena in which the funding takes place (Sherman and Dergis, 1981). There are three main characteristics that

Sherman and Dergis considered as the most critical building factors: 1) the size or extent of the physical plant, 2) the complexity of the plant, and 3) the age and history of the plant. In order for a formula to accurately ascertain the amount of the budget needed, it must account for all of these factors (Sherman and Dergis, 1981). Sherman and Dergis further state that formulas that have to operate in a political environment (where a governing funding body makes appropriation decisions) must also be generally applicable, simple to apply, easy to understand, self-adjusting, and reliable. The budget value attained must be an index-inflated adjustment of the original cost of construction and of the building's age corrected for partial building renovations (Sherman and Dergis, 1981).

The Sherman-Dergis formula for a facility or infrastructure item is expressed by the following:

Annual M&R Appropriation = 2/3 * BV * BA/1275

where:

"Annual M&R Appropriation" is the amount of funding that should be provided in a given year of the facility's life for M&R maintenance,

"2/3" is the building renewal constant as determined by a 1971 University of Illinois study which showed that building renewal ought to cost, on the average, no more than two-thirds of the cost of new construction (Sherman and Dergis, 1981).

"BV" is the building value as determined by updating the original construction costs using a recognized national building cost index, “BA” is the building age as corrected for either partial or total building renewal, and

“1275” is the age-weighting constant based on a fifty-year lifecycle. This number is derived from the sum-of-the-years digits depreciation method.

The key relationships from the Sherman-Dergis Formula approach are the relationships between inflation corrected construction cost, facility current age, and the building renewal factor to the annual M&R budget figure. Here, as before with the PRV method, there is no direct link between facility condition and the budget determination, lending to the same criticism as the PRV method.

Life-Cycle Methods

The life-cycle estimation method depends on breaking the facility down into subsystems (Melvin, 1992). Common subsystems include electrical; Heating, Ventilation, and Air Conditioning (HVAC); roofing; and exterior cladding. The level used is once again dependent on the desires of the individual modeler. Through the independent determination of the life-cycle for each subsystem, the known cost of their respective preventative maintenance tasks can be derived. Using the derived tasks, further estimation of the M&R budget can be obtained by estimation of each individual task. The result of the estimation is taken to represent the annual M&R costs for the entire facility (Melvin, 1992). This method requires immense amounts of detailed data for each facility to be considered. It is very facility dependent, and universal simulation applications are not practical.

Condition Assessment Methods

The condition assessment method of determining M&R costs uses an actual condition survey of the facility to identify needed repairs. Then a detailed cost estimate is prepared for these repairs. The estimation of these repairs is then taken to represent the annual M&R budget. The bottom line is that degradation of the facility has occurred and must now be repaired. There are two aspects of the assessment process that might be used independently or together. The first aspect depends not only on the current needs of the facility, but also attempts to predict future needs or repairs and capture their costs in the estimate as well. The second aspect uses a backward-looking approach that includes the estimate of the previous year's deferred M&R actions and the immediate needs to determine the estimate for annual M&R costs (Ottoman, 1999).

The framework for a condition assessment is the index that the assessment uses for measurement of the infrastructure or facility. Most approaches define the condition index of a given facility in terms of the facility's ability to perform its intended function or a user-defined function (Chouinard, et al, 1996). In order for this assessment to be practical, it must take visual observations, instrumentation readings, operational information, engineering computations, and/or engineering judgments, and, through the use of predefined rules, convert those observations into numerical values known as condition indices (Chouinard, et al, 1996). This condition assessment then provides a snapshot of the facility condition in time (Chouinard, et al, 1996).

There are several different published and established indices for facilities and infrastructure. They include the pavement condition index (PCI) (Shanin, Darter, and Kohn, 1976; Shanin and Kohn, 1979), the roofing membrane condition index (MCI), the roof flashing condition index (FCI) (Shanin, Bailey, and Brotherson, 1987), clay brick masonry walls (Uzarski et al, 1995), concrete masonry walls (Uzarski et al, 1995), and exterior closure components or the exterior finish (Uzarski et. al, 1995). Inspections using these indices are conducted on a schedule prescribed by the user and maintainer to identify when and where facility and infrastructure maintenance must occur. Uzarski et al (1995) discuss that the data gathered produces a candidate list that can be used to produce a budget that is defendable.

The key relationship in the condition assessment approach is between the facility degradation and the budget determination. There are very important assumptions in the condition assessment method that make the method possible. The assumptions are (Uzarski et. al, 1995):

> "Condition is a measurable attribute.
> Raters are capable of making quantitative judgments about condition.
> The judgment of each rater can be expressed directly on an interval scale.
> Variability of judgment is a random error.
> Raters are interchangeable (equally capable of making the required judgment of condition).
> Averaging individual rating values can be used to estimate rating scale values."

By honoring these assumptions (and through the above relationship) the method produces a budgetary figure for infrastructure and facility maintenance.

Budget Manipulation

Once the basis for the M&R budget model is chosen, it then becomes necessary to adapt the budget to the changing environment. Inflation, age of the facility, and degradation are just a few of the reasons to continually adjust the baseline budget. Barco (1994) offers four approaches that are commonly used, a based-budget model, zero-based-budget model, budgeting by project backlog or budget based on facility attributes

(Barco, 1994). He also identified identified two types of facility attributes that need to be considered when adjusting the annual budget. They are best described as fixed and variable attributes. Table 2 captures the description of each type.

Table 2 Facility Attributes

Fixed Attribute	Variable Attribute
Location	Size
Facility Type (building, utility, road, etc)	Capital Improvements
Year Acquired	Current Value
Acquisition Cost	Replacement Value

Fixed attributes are stable with time; therefore they have little impact on the annual budget once the baseline is determined. The trends of the variable attributes drive the M&R costs predictions up and down. The variable attribute trends provide the supporting justification for the changes to the annual M&R budget variations (Barco, 1994).

Based-Budget Model

This adjustment method is also known as the ramping approach. The based-budget model involves the determination of a baseline budget figure and then increasing that baseline annually by a percentage to match inflation. The method falls under criticism after several years of use, because at that point, the budgetary figure has lost its correlation with actual M&R requirements. The simplicity of the model, however, makes the approach popular. Recent automation advances have increased the accuracy of other methods and made them easier to use; thus, the based-budget model is starting to lose favor (Barco, 1994).

Zero-Based-Budget Model

Zero-based budget models re-justify the base each and every year. While providing an accurate picture of the actual budget, this method is prone to wide funding swings. Zero-based budget models introduce a concept of acceptable M&R backlog. Managers are allowed to manipulate an acceptable level of incomplete M&R tasks or backlog acceptable to their respective organization (Barco, 1994).

Budgeting by Project Backlog

The project method of budgeting focuses more on the projects than on the attributes of the facility. The facility's list of required M&R projects can often exceed any budget, creating a backlog of work that must be managed. Therefore, emphasis must be placed on prioritization of the projects by upper level management. The backlog of projects needs to be continually manipulated by management. At times, management may decide to compile several small projects into larger comprehensive projects. The emphasis on projects over the attributes makes the accuracy of the project's cost estimate very important. Inaccurate estimates can result in either not enough work being scheduled or too much work being scheduled (Barco, 1994).

In combining Ottoman's (1999) four methods of budget determination with Barco's (1994) methods of budget manipulation (or updating), one is left with the matrix shown in Table 3. Every method of budgeting M&R requirements covers areas of the matrix. The amount of coverage varies with the individual model. By using this matrix, the budget models to be evaluated can be classified.

Table 3 Budget Determination Methods and Budget Manipulation Models Matrix

	Facility Attributes	Based-Budget Model	Zero-Based-Budget Models	Budgeting by Project Backlog
Plant Replacement Value Methods				
Formula Based Methods				
Life-Cycle Methods				
Condition Assessment Methods				

Depreciation/Facility Degradation Modeling

No one argues that facilities degrade. Facilities degrade as a result of many different factors. Age and use are the leading contributors (Barco, 1994). Modeling degradation is a complex problem. Several concerns arise when degradation is simplified for modeling deterioration as a stochastic process (Durango-Cohen, 2004). Modeling techniques that use Markovian models that are stationary in time are examples of these over simplification assumptions (Durango-Cohen, 2004). Guillaumot et al. (2004) extended a methodology to account for the uncertainty in measuring facility condition using the Markov decision process. They were able to account for the inherent randomness of facility deterioration through the use of transitional probabilities. This methodology captures a great deal more of the uncertainty around facility degradation than models utilizing straight-line depreciation methods or sum-of-the-years-digits methods (Canada, 1980). The Guillaumot Markovian model assumes the data necessary to perform it is readily available (Durango-Cohen, 2004). Unfortunately this assumption carries a heavy price tag in money and time necessary to collect reliable sets of data, thus placing a limit on its effectiveness, particularly in simulations (Durango-Cohen, 2004). Never the less, the need for a degradation model exists to accurately evaluate the performance of M&R budget models in a dynamic environment. As a result, the earlier presented matrix gains a third dimension. As shown in Figure 3.

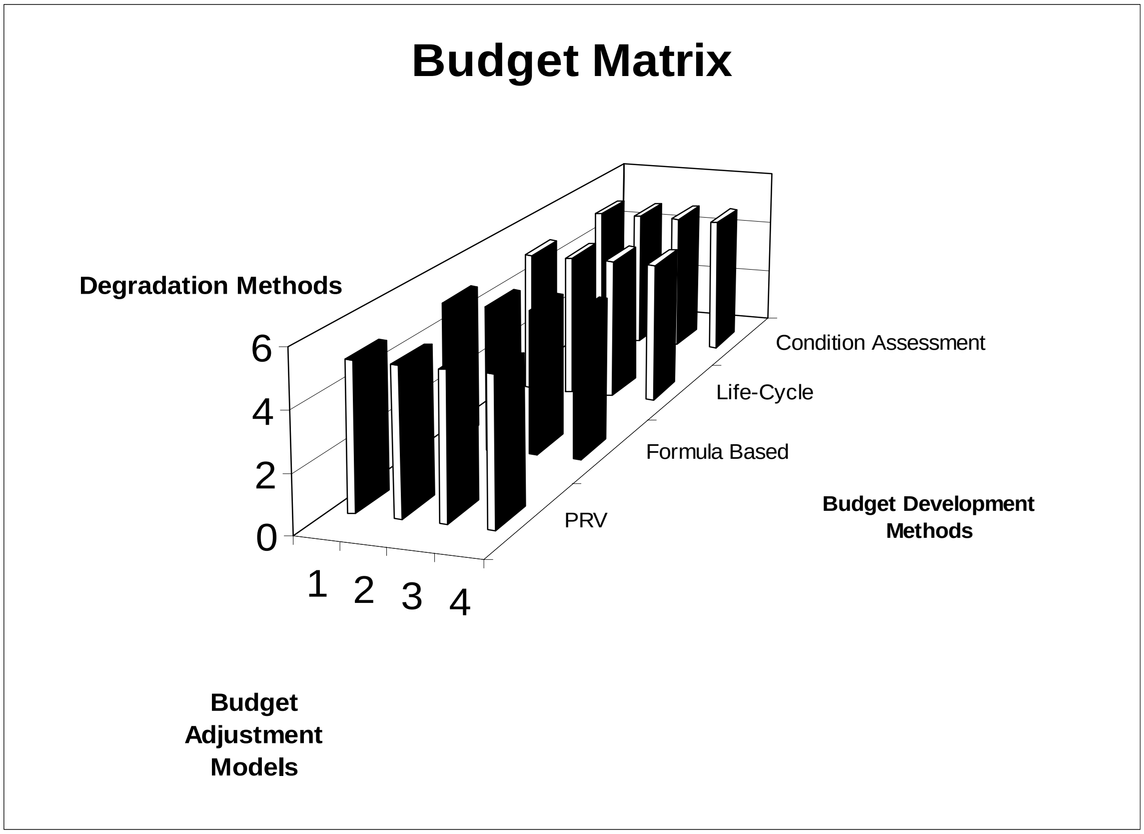

Figure 3 Budget Three Dimensional Matrix

By gaining a proper understanding of the tools and methods for M&R budgeting and the modeling of base infrastructure and facility degradation, the evaluation of the various techniques can be accomplished. Without an in depth understanding of these methods, the Air Force civil engineer would have a difficult time developing a tool to measure the performance of any budgeting method. The Air Force continues to train, equip, and fight from an aging infrastructure. It is paramount that its maintenance personnel posses the knowledge of these methods and understand how to properly evaluate them.

III. Methodology

The methodology for this study is based on a system dynamics approach to provide a dynamic evaluation of various recurring infrastructure maintenance funding methods. System dynamics is a methodology for studying and managing complex feedback systems (Daum, 2001). This methodology's design focuses on the behavioral pattern of the outcome of a complex system of relationships or influences, which are so strongly interconnected that the study of an isolated individual component would cause misrepresentation of the outcomes and would not be representative of the entire system. Forrester (1985), the chief proponent of system dynamics since the 1960s was quoted, "The value of a model lies not in its predictive ability alone but primarily in the learning generated during the modeling process." Therefore, the end determinant is to provide the studier an in-depth understanding of the relationships and influences in the system, a means to manipulate controllable variables or parameters within the system, and a means to simulate and predict the impact of parameter changes on the outcome behavior. The conclusions of system dynamics studies are sometimes strikingly different than the conclusions drawn from studies done on individual components of the system (Daum, 2001).

Rationale for the Study

The rationale for this study is based on creating a dynamic evaluation tool capable of simulating the relationship between maintenance actions, maintenance budgets, degradation, and serviceability of a facility or infrastructure throughout the facility's or infrastructure's lifespan. This dynamic study should accomplish the following goals. First, the study should accomplish the goal of providing the Air Force civil engineer a dynamic evaluation tool for the analysis and development of maintenance budget strategies that are capable of prolonging infrastructure and facility life at a satisfactory level of serviceability to meet mission objectives. Secondly, the study should accomplish the goal of interpreting the output of the model simulations. The interpretation of the evaluations should present a behavioral difference for evaluating various facility and infrastructure maintenance budget strategies in current use in facility and infrastructure maintenance today. Thirdly, the study should make recommendations as to how a facility-specific dynamic method can be developed that substantially improves serviceability of Air Force facilities and infrastructure, thereby giving a more accurate picture of the cost of incomplete preventative maintenance.

Instruments of Data Collection

The instruments for this study include a review of current literature on facility maintenance methods and evaluation techniques, and the development of a dynamic simulation and evaluation model for facility and infrastructure maintenance budgeting methods using a system dynamics approach.

Modeling Technique

The system dynamics approach to modeling can be broken into four distinct phases. The first phase is conceptualization, which is best characterized as building a mental picture of the model. Second is the formulation, where the model is written down in a form that can be evaluated. Third is the testing phase that exercises the model through the full range of values. Fourth and lastly is the implementation of the model in which the output is accepted by the end user as valid for prediction. Once accomplished in an iterative process (not merely a sequential order), these four steps yield the modeler a dynamic tool for evaluating the system. These phases are summarized and described in Table 4 (Shelley, 2004).

Table 4 The Four Phases of Model Construction

Phase	Description of Elements
Conceptualization	Familiarization with the general problem area Definition of the question to be addressed—either, What caused a given development? Or, What are the likely effects of a given policy? Description of the time development of interest (the reference mode)—defining the time horizon and the range of time constants in the model. Verbal description of the feedback loops that are assumed to have caused the reference mode (the basic mechanisms)—defining the system boundary and the level of aggregation. Development of powerful organizing concepts. Description of the basic mechanisms in causal diagram form.
Formulation	Postulation of detailed structure—selecting levels, selecting rates and describing their determinants. Selection of parameter values.
Testing	Testing of the dynamic hypothesis—Do the basic mechanisms actually create the reference mode? Testing of model assumptions—Does the model include the important variables? Are the assumed relationships reasonable? Are parameter values plausible?
Implementation	Testing of model behavior and sensitivity to perturbations Testing the response to different policies. Identification of potential users. Translation of study insights to an accessible form. Diffusion of study insights.

Phase I: Conceptualization. The modeler must stay focused on the behavior throughout this phase. In the conceptualization phase, it is necessary to become familiar with the general problem. Paramount to any methodology is clearly defining the question to be evaluated by seeking out what has caused the given development and what are the likely effects of a given change. After conceptualization, the next step is to define the reference mode or the time horizon for the study and the range of the behavior over the time horizon. The reference mode is defined as the desired or end state behavioral pattern that is to be achieved and is most commonly graphically represented with the dependant variable portrayed on the *y* axis with *x* axis representing time. Also involved in conceptualization is the description of the feedback loop framework that is assumed responsible for the reference mode. Lastly in the conceptualization phase is the description and assembly of the basic structures of the causal diagram. The basic structures are composed of stocks (or accumulation points) and flows (or the mechanistic representation) that increases or decreases the stock at a prescribed rate through five generic flow processes. The five generic flow processes are compounding, draining, production, coincident flow, and stock adjustment. The arrangement of the basic structures is directly related to the respective behavioral outputs. The end state of the conceptual phase is the formation of the reference mode and causal diagram (Shelley, 2004).

This phase of the process is most often the most critical and time consuming phase of the entire process. It requires the modeler to compile the most information through documentation of methods and processes or through direct interaction with those familiar with the methods and processes. Beginning modelers can often fall prey to the most common mistake in this phase as well. The desire to try to describe the real world and create a depiction of reality shown by flow diagrams rather than staying focused on the behavior of the system can derail even the best modeling effort (Shelley, 2004).

Phase II: Formulation. During the formulation phase, the modeler details the structure given the established reference mode behavior from phase I. The modeler accomplishes the formulation by assigning levels, rates, and descriptions of their determinants. The modeler also establishes, describes, and defines all parameter values. The modeler must pay close attention to maintaining consistency among the units used in the system. The modeler faces a heavy amount of iteration in this phase (Shelley, 2004).

Phase III: Testing. The testing phase is sub-divided into two major categories of testing: testing the dynamic hypothesis and testing the model's assumptions. The ultimate goal in testing the dynamic hypothesis for the modeler is evaluating the ability of the basic mechanisms within the structure to actually produce the expected reference mode. In the second portion of testing, the modeler is checking for the inclusion of all pertinent variables, the correctness of the relationships, and the correctness of the parameter values (Shelley, 2004).

Phase IV: Implementation. In this phase of the modeling process, the modeler seeks to gain validation of the model by end users. This is accomplished by testing the model's behavior and sensitivity to internal and external influences, demonstration of various policies, correct identification of potential users, and understandable translation of garnered insights about the system (Shelley, 2004).

Subject Population

The subject population for this study is a representative group of maintenance budget strategies for facilities and infrastructure. The maintenance budget strategies of interest are those found to be commonly practiced in facility and infrastructure maintenance by organizations or firms that have a large number of facilities or an infrastructure plant. Government agencies like the DoD, major universities, and large corporations are the major players.

Data Collection

The data collection process for this study was done using a computer simulation process. The system dynamics model that was constructed using the above technique was electronically coded into simulation software. The simulation software is the STELLA Research version 8.0 software program (High Performance Systems). STELLA conducts iterations of the system and represents the system's behavior over the prescribed time. For this study, the research period was 100 years. The study length was determined after considering that average facility length is 30 to 70 years (Lemer, 1996). The various budgeting methods were simulated over this time period against varying degrees of degradation to produce comparative behavior patterns. The modeler or researcher then discusses the findings from the comparisons and insights gained into the complex system.

IV. Results

Model Conceptualization

The system dynamics methodology for this study started with the conceptualization phase. During this phase, the problem was clearly defined. Specifically, missed or scheduled maintenance cannot be made up if it is missed then the value of the maintenance action is lost. If the degradation that would have been corrected by maintenance is allowed to go unchecked, what is the ultimate impact of the situation on the facility or infrastructure?

It is necessary to define the terms and key assumptions that will be used throughout this discussion: serviceability and degradation. Serviceability is the measurement of a facility's or infrastructure's capability to meet its mission requirement. Conversely degradation is the wear and tear that has reduced the facility's capability to perform a given mission. It is assumed that one unit of serviceability is equal to one unit of degradation. These two terms are also assumed to have a complementary relationship. That is, if a facility has a total value of 100 serviceability units, then the sum of remaining serviceability plus degradation equals 100. This is represented in the following equation.

$$\text{Remaining Serviceability} + \text{Degradation Occurred} = \text{Initial Serviceability}$$

This is a key relationship and assumption for the modeling process.

The second key assumption is that every infrastructure item has a finite value of Initial Serviceability which can be degraded. This value can be assumed or there would be no need for the infrastructure item to exist. Degradation takes away from this value, and maintenance actions replace what has been degraded. In order to create additional serviceability, one must complete a major renovation or construct an addition. The serviceability value of a facility can be quantified, but it is extremely difficult to measure. Further, initial serviceability is difficult to assign. For example, justification of assigning a value of 200 units to an aircraft shelter and 150 serviceability units to the electrical distribution system utilizing the same scale is very difficult. Therefore, for the purposes of this modeling research, the value of total serviceability will be normalized for any given facility to 100 serviceability units regardless of the facility type or mission.

The monetary value of each unit of serviceability also must be established. The assumption will be made that the monetary value (dollars) of a unit of serviceability can be determined by taking the construction replacement cost of a facility and dividing it by the initial serviceability. This gives a measure with units of dollars per serviceability. To account for varying costs of facilities within the modeling process, the cost of all facilities will be normalized. Each facility will be assumed to have a monetary value of 100.

The next step in the conceptualization phase is hypothesizing the facility's serviceability behavior pattern over time; in other words, the next step is to create the "reference mode". In research question 3 of Chapter I, the need for understanding the typical lifecycle serviceability behavior pattern for base infrastructure and facilities was stated. The initial ideas of how this hypothesized behavior are shown in Figure 4.

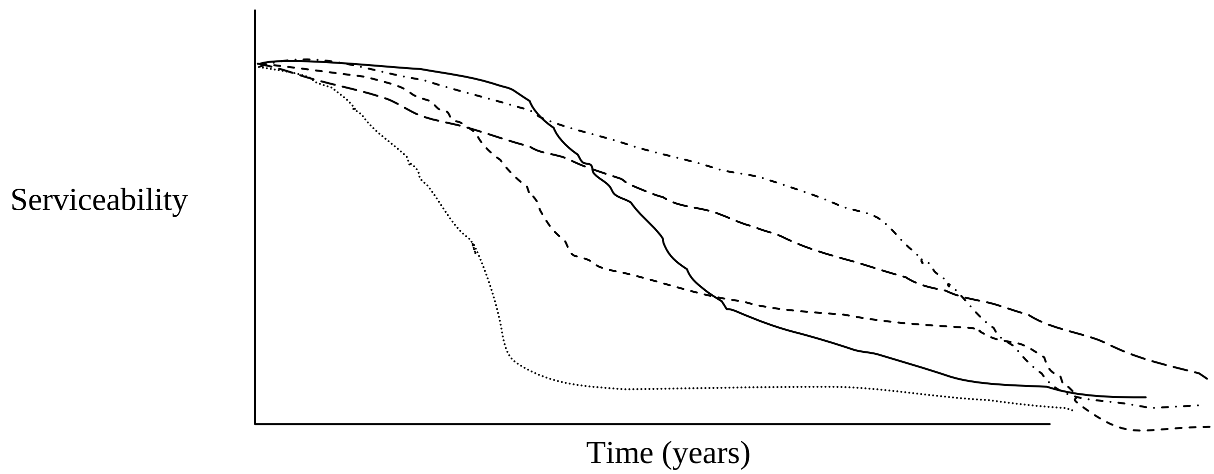

Figure 4 Conceptual Alternative Behavioral Patterns of Serviceability vs. Time

This hypothesis comes from the author's experience in dealing with facility maintenance over the past ten years. The patterns suggest that facilities and infrastructure have an initial phase of life where they degrade slowly. In this initial phase, the facility or infrastructure is new and needs only small amounts of maintenance to correct the degradation occurring. This is followed by a phase of rapid decline as degradation increases at a rate that overtakes the impact of maintenance actions. The end of the lifecycle is portrayed as a phase of slow degrading as the facility awaits renovation or demolition and final disposal. This concept was further supported by Lemer's (1996) diagram as discussed in Chapter II. Adapting Lemer's (1996) diagram, assuming that serviceability is an equivalent term to performance, produces the following diagram shown in Figure 5.

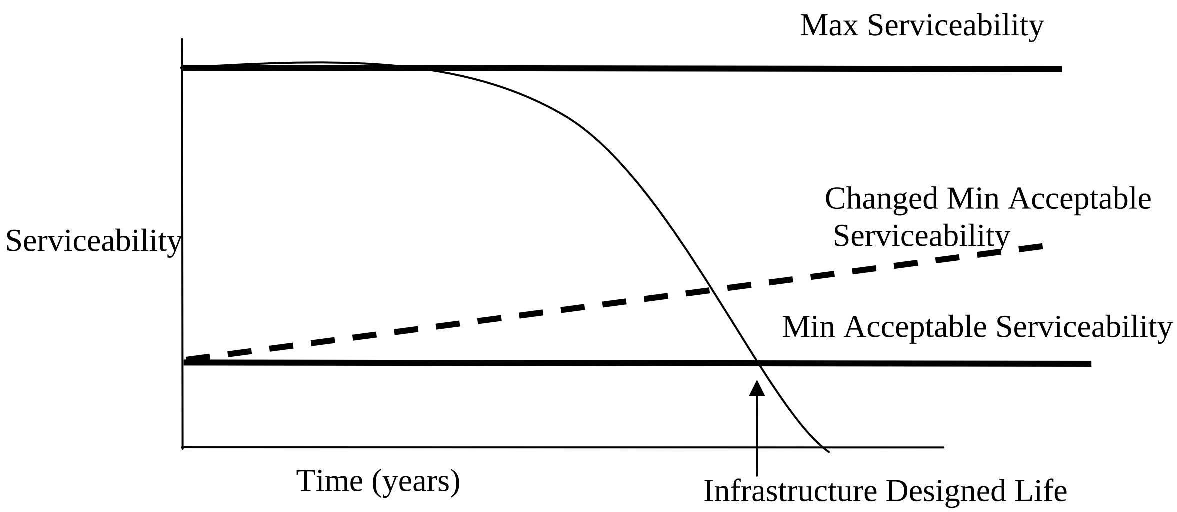

Figure 5 Lemer Behavioral Pattern Seriveability vs. Time

Lemer's (1996) diagram further supports the initial phase of slow degradation followed by a rapid decline. Lemer also adds the maximum serviceability and minimum acceptable serviceability levels. The maximum serviceability line is the same as the initial serviceability for the facility. The minimum acceptable serviceability for the facility is defined in Air Force programming policy. The Air Force policy is that if the total cost of the repair work programmed against a facility exceeds 70% of the total cost of the facility, then programming should be done for replacement rather than repair. This provides a suitable proxy for the minimum acceptable level of serviceability. The minimum acceptable serviceability level will be assumed at 30% of the total facility or infrastructure serviceability. Therefore, we have the declining S-shaped reference mode behavioral pattern for the modeling effort is shown in Figure 6.

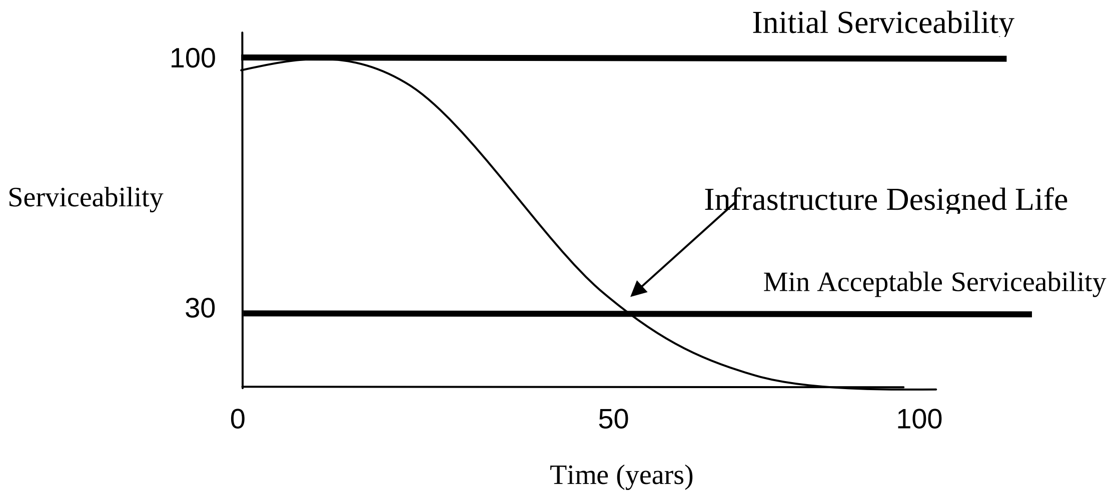

Figure 6 Reference Model Serviceability vs. Time

Implementing system dynamic's methodology; the influence or causal diagram (system influence structure) follows from the behavioral pattern. Keeping focused on the S-shaped decline of serviceability, the dynamic model is developed in small portions. Each small portion is then moved through the remaining three phases rather than trying to produce the entire model in one pass.

Using the reference mode, the system dynamics causal diagram is built using the basic structural causal mechanisms. There is not a basic mechanism for this pattern. However, the degradation complement relationship with serviceability creates an S-shaped growth pattern for degradation. The complementary relationship is shown in Figure 7.

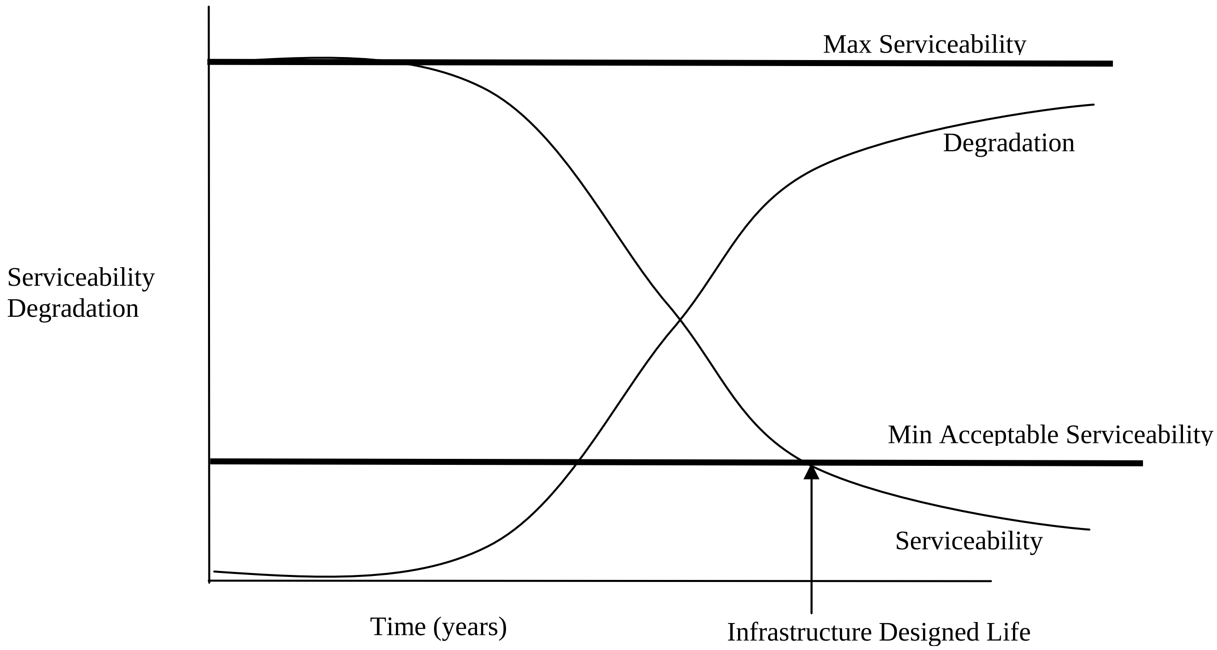

Figure 7 Reference Mode Serviceability and Degradation

The system dynamics mechanism for the degradation S-shaped growth is represented by the influence diagram in Figure 8.

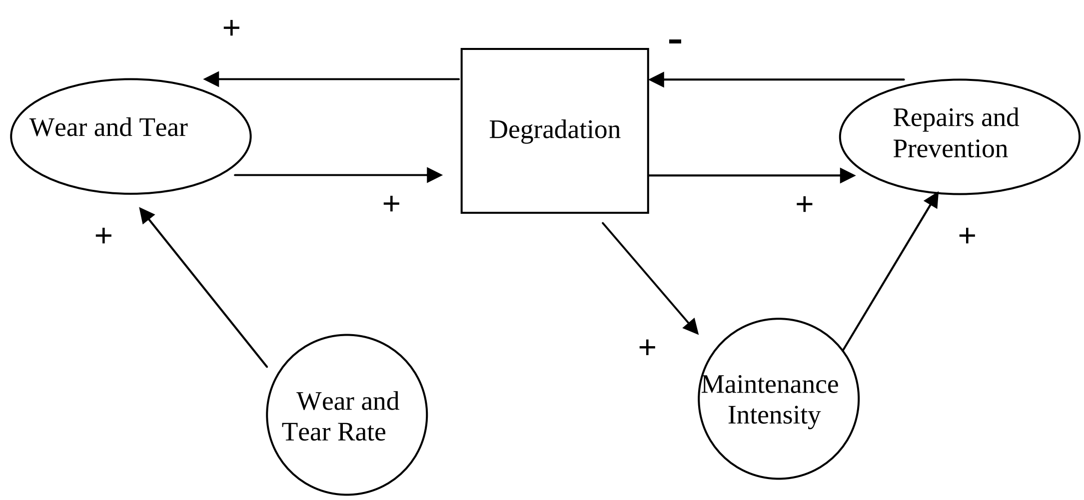

Figure 8 Influence Diagram

This influence diagram is then programmed into the STELLA software, with the output being shown in Figure 9. Note the rate constant takes the label wear and tear rate.

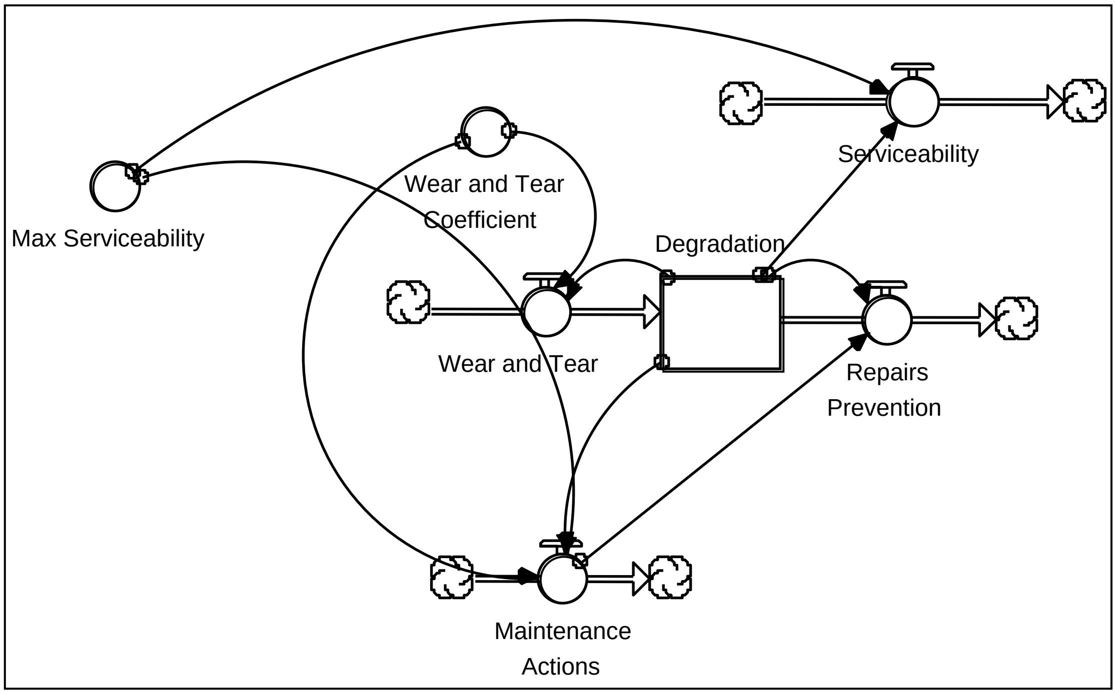

Figure 9 STELLA Flow Diagram

The literature review revealed various formulations for degradation based on financial depreciation methods and statistical failure models. These formulations are not consistent with the behavioral pattern observed for infrastructure degradation above. These depreciation formulations are front-loaded, and rapidly increase in the initial phase, and then slowly tail off later in the life cycle. Therefore, these formulations are unsuitable for accurately modeling degradation. Instead, this model uses a logistics equation for degradation:

$$dDRG / dt = r * DRGt * (1 - DRG_t / DRG_{max})$$

t = Time
DRG = Degradation
DRGt = Degradation at time t
DRG_{max} = Degradation Maximum
r = Degradation (Wear and Tear) Rate

In creating the STELLA flow diagram, the maintenance actions act as a flow; therefore, a converter was necessary to allow for further growth of the model. Maintenance actions is represented as a standalone flow entity that will allow for the budget method to be constructed around it. After running the simulation, the behavior produced is shown in Figure 10.

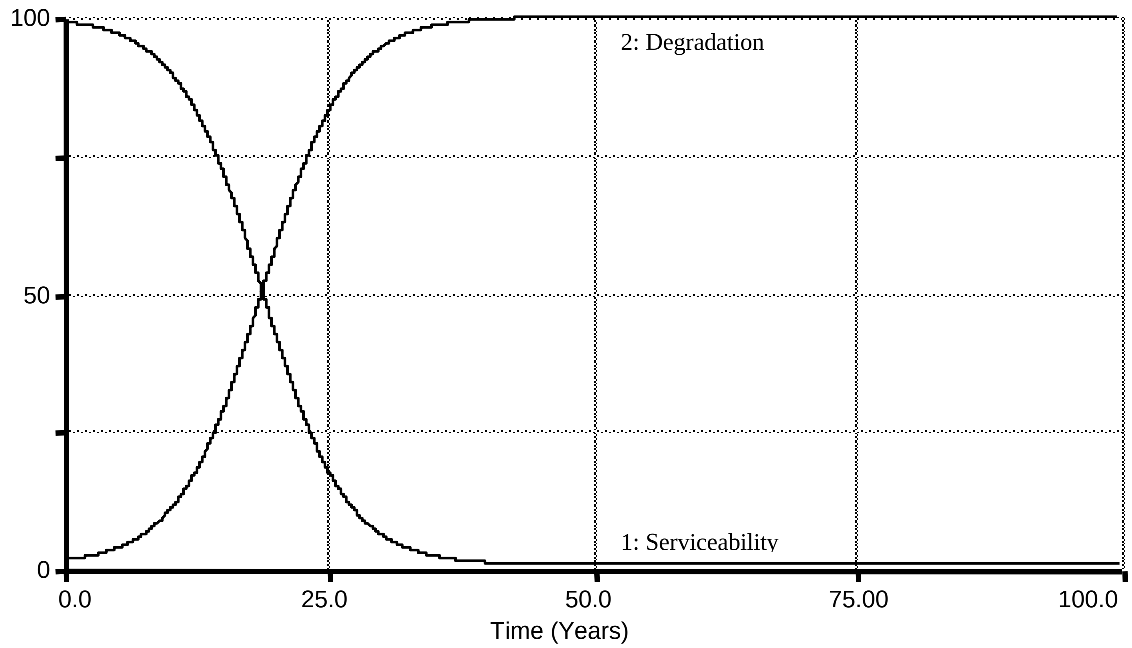

Figure 10 Serviceability and Degradation Output

The output of the simulation matches the reference mode. Therefore, we can conclude that the model is performing as expected. To further validate the model, it is necessary to test the wear and tear rate parameter through sensitivity analysis. This is accomplished by running the model simulation through the full range of the wear and tear parameter. The results of the sensitivity testing are shown in Figure 11.

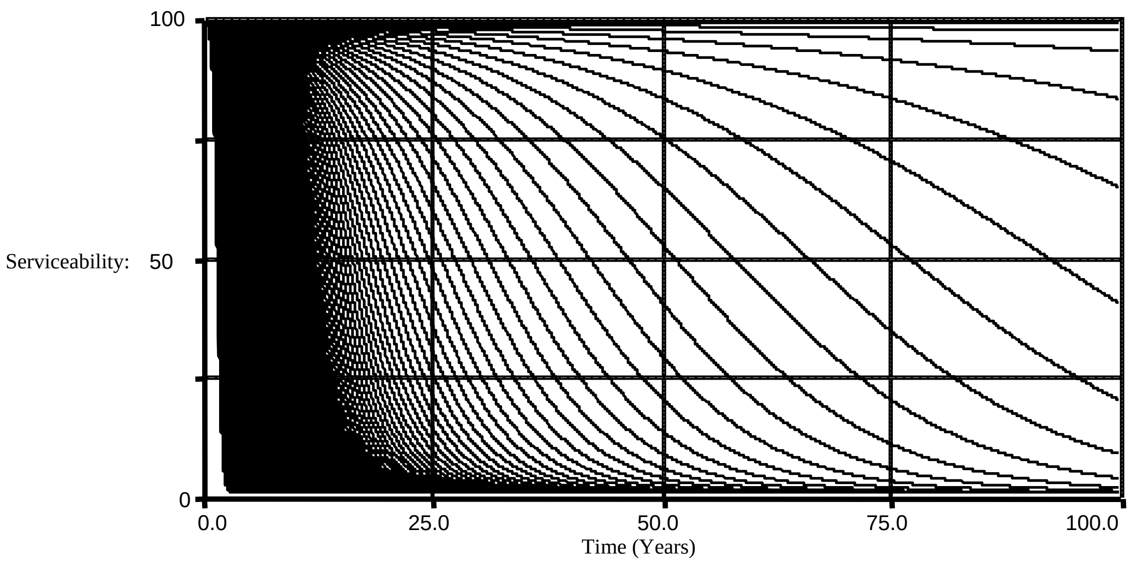

Figure 11 Wear and Tear Rate Sensitivity Analysis

Important to note about Figure 11 is that the underlying shape of the pattern remained unchanged; only the slope and curve radius were impacted by changing the value of the parameter. As the wear and tear rate increases, the slope increase, the curve radius decreases, and the life span is decreased. As the wear and tear rate decreases the slope decreases, the curve radius increases and the life span increases. The wear and tear parameter was utilized to get a facility behavioral pattern that would, under unlimited budget conditions, produce a facility that, at 50 years service, would have retained 30% of the Initial Serviceability of the facility. This is to say that the facility or infrastructure item reached its designed life span as shown in Figure 12. Therefore, the scaling parameter is set for the model of the system to perform in the time frame of interest.

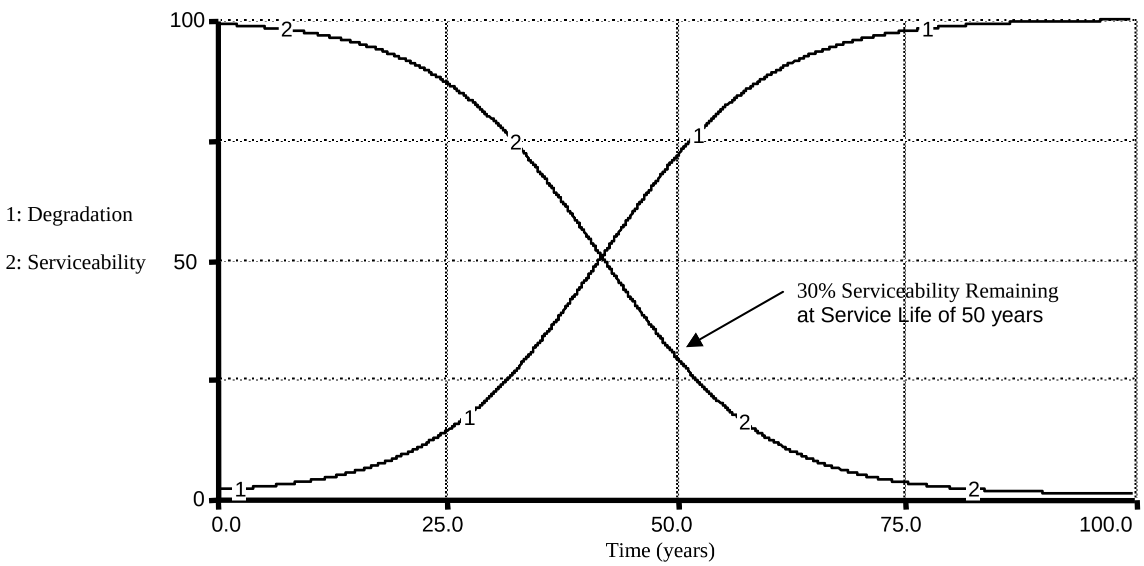

Figure 12 Refined Serviceability and Degradation for 50 year life span

The next step is the inclusion of the budget determination methods in the model. These infrastructure maintenance budgetary methods were discussed in detail in Chapter 2. The maintenance methods to be included and evaluated by the model are 1) the Air

Force's chosen method of PRV, 2) the condition assessment method, 3) the Sherman-Dergis formula method, and two control methods: 4) no-maintenance and 5) the unlimited budget method. These five facility maintenance budget methods will be the test subjects for the dynamic evaluation model. As such, the maintenance budgets determination strategies also answer the first research question (what budget maintenance strategies exist?).

These budgetary methods give way to relationships within the system of facility and infrastructure maintenance. These relationships were mentioned in Chapter II's discussion of the individual methods. From these relationships the start of a relationship diagram can be developed. Figure 13 represents these relationships and the feedback loop they create. Figure 13 represents the influences within the facility maintenance system through the use of arrows. Overall, this diagram serves as a baseline since it is based on existing literature regarding the various budget methods.

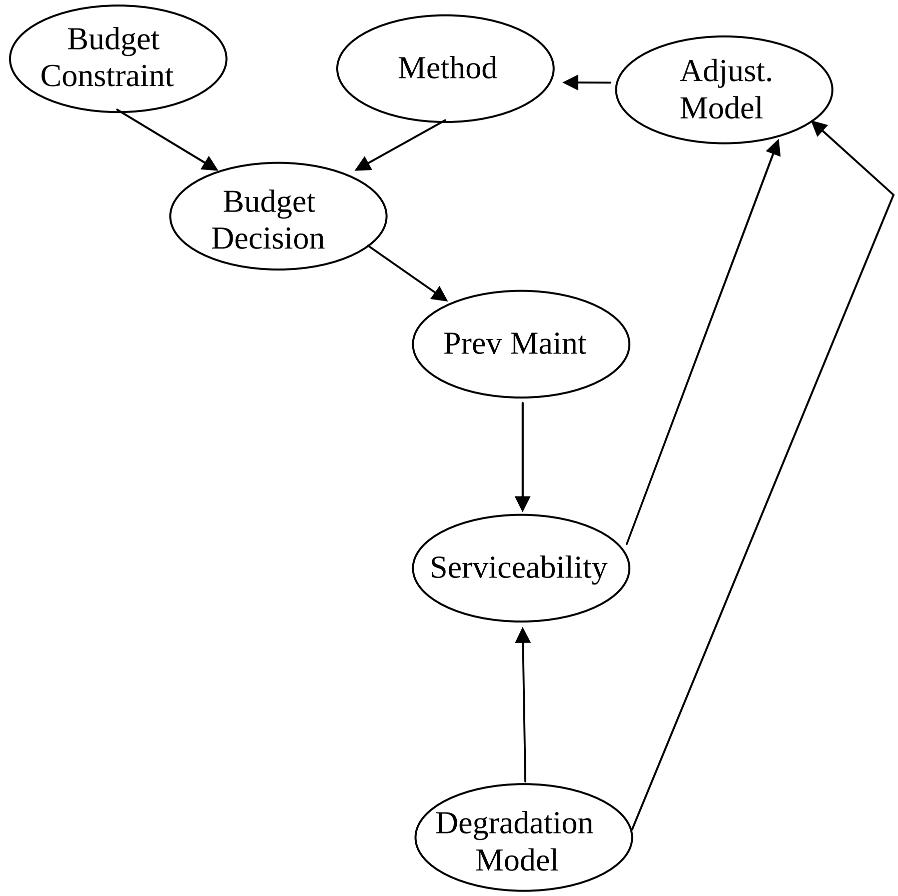

Figure 13 Relationship Diagram

The basic evaluation model is constructed and the next step is to code the budget development methods into STELLA. Note that the budget development methods structures are not dependent on the behavior pattern of degradation, but rather on the method's authors who set up the internal relationships to establish how the method determines the amount of funding required. Inclusion of the methods to the model produces the final flow diagram from STELLA as shown in Figure 14. Once the budget methods were included in the dynamic model, a user interface was created that would allow the tester to manipulate management decisions within the respective budget methods to be tested.

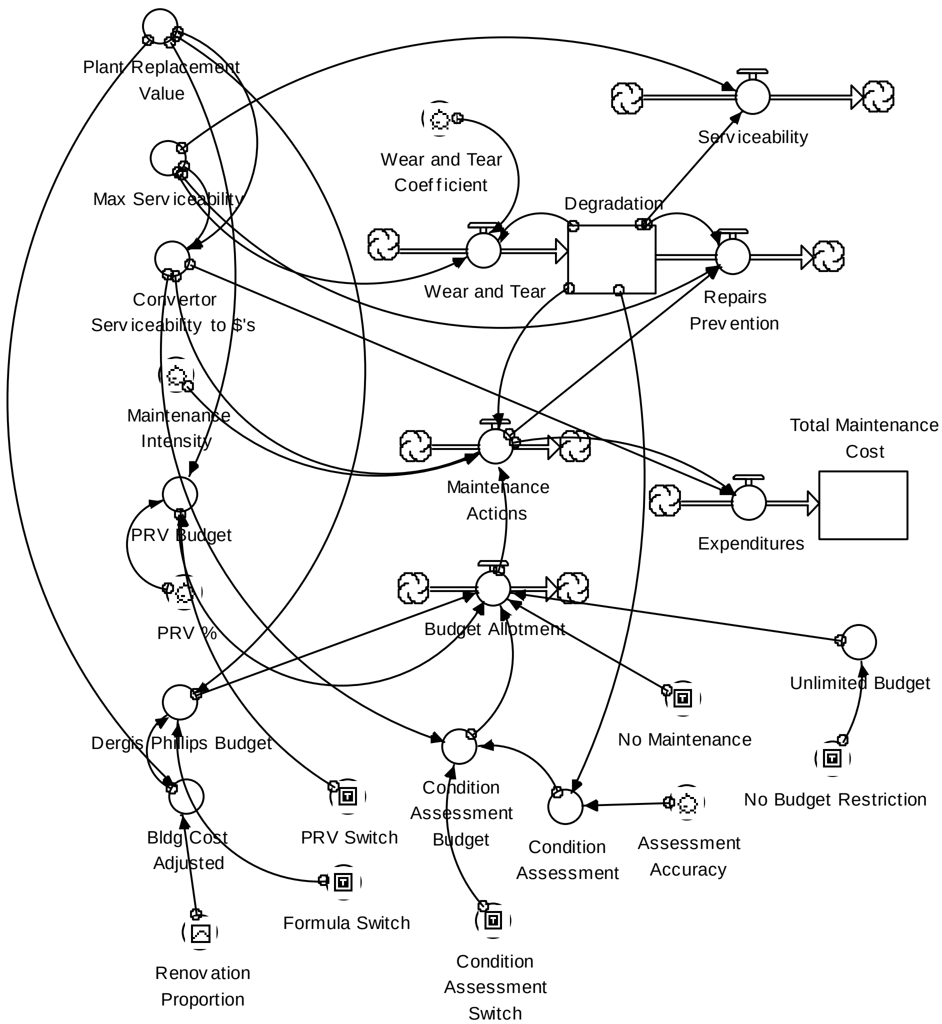

Figure 14 Full Model STELLA Flow Diagram

From the literature review, the answer to research question four produced the different controlled influences for each individual method. For the PRV method, the focus control is the percentage of the plant value that would be budgeted for maintenance. Thus, the user is allowed to manipulate this value within a range of 0% to 10% based on the range found in the literature. Within the condition assessment method, management controls the time and effort put into the assessment itself. Therefore, management indirectly impacts the accuracy the assessment achieves. The model allows the user to manipulate the level of accuracy for the assessment. Lastly, within the Sherman-Dergis formula, the assumption of a 2/3 infrastructure renewal rate is made based on standard industry practices. This assumption is management driven; therefore, the control for the formula method is to vary this renewal fraction. The two control methods have no management control variables. The policy that management sets has a direct control on their budgeting and execution process. The final flow diagram of the model, formulations, and user interface are shown in Appendix A. It is now possible to show, through sequential simulation, how these controllable influences impact the infrastructure.

In evaluating the various methods, a test range was set up for each method. The range of the controllable input was established for each method from the literature. The exhaustive sets of test results for each method are shown in Appendix B. These results are shown with varying degrees of degradation by changing the wear and tear rate which represents varying facility types, usage levels, and climatic zones - all of the facility and infrastructure attributes put forth by Barco (1994) in Chapter II. The following is a comparative graph showing the serviceability behavioral pattern for each of the five methods (see Figure 15). The first overarching conclusion clearly seen from the graph is that none of the methods stop degradation from occurring.

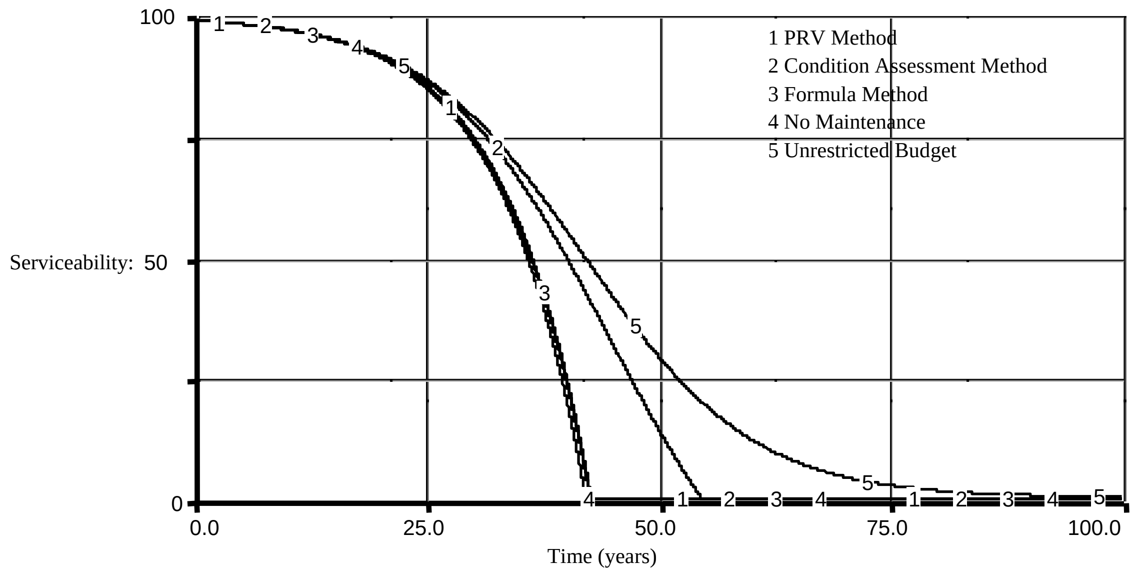

Figure 15 Comparative Serviceability

In order to control the growth of degradation, the maintenance budget has to be extremely high and disproportionate to the replacement cost of the facility, thereby making it impractical for facility owners and maintainers to consider. Therefore, it is unrealistic to desire a budget method that stops degradation. Instead, the desire needs to be for a budget method that maintains serviceability above the minimum acceptable serviceability throughout the life span of the facility.

The next overarching conclusion the test results show is that all of the budgetary methods fall short of reaching the designed lifespan. This includes the Air Force's PRV method. The alarming part of this conclusion is that in the initial phase of the facility's life, the budget methods perform equally and appear to be performing at a level that will allow the facility to meet the desired serviceable life. These misleading results are particularly concerning because, once the degradation growth starts to outpace maintenance operations, it is nearly impossible for the maintenance actions to make up the lost ground without it becoming cost prohibitive. These results clearly highlight the importance of preventive maintenance. It is paramount to keep up with degradation even though you cannot stop it. Degradation must be contained early, or it will have a synergistic growth rate and compound beyond maintenance control.

Presently, this is true of the Air Force budgetary method. The Air Force uses a 1.4% PRV for facility and infrastructure maintenance and repair budgeting, thus answering research question number five. In the initial phase of the infrastructure's life cycle, the 1.4% PRV looks to be capable of sustaining the facility serviceability for its entire life span. However, as the age of the facility moves out past the 25-year mark, the ability of the budgeted maintenance to sustain the serviceability is inadequate and the facility's degradation starts to grow almost unchecked. This creates a situation in which the ability of the facility to meet the mission requirements is diminished to the point of direct mission impact, or worse, failure. Therefore, the answer to research question six (is the policy preserving the infrastructure for mission objective sustainment?) is no. Furthermore, detailed examination of the Air Force PRV method shows that it can be increased ten-fold and still not maintain the minimum acceptable serviceability for the facility's entire life span. This is reflected in Figure 16 in which the PRV is varied from 0.25% to 10%. However, a second look at Figure 15 does show that the Air Force's PRV budget method out performs the other methods tested.

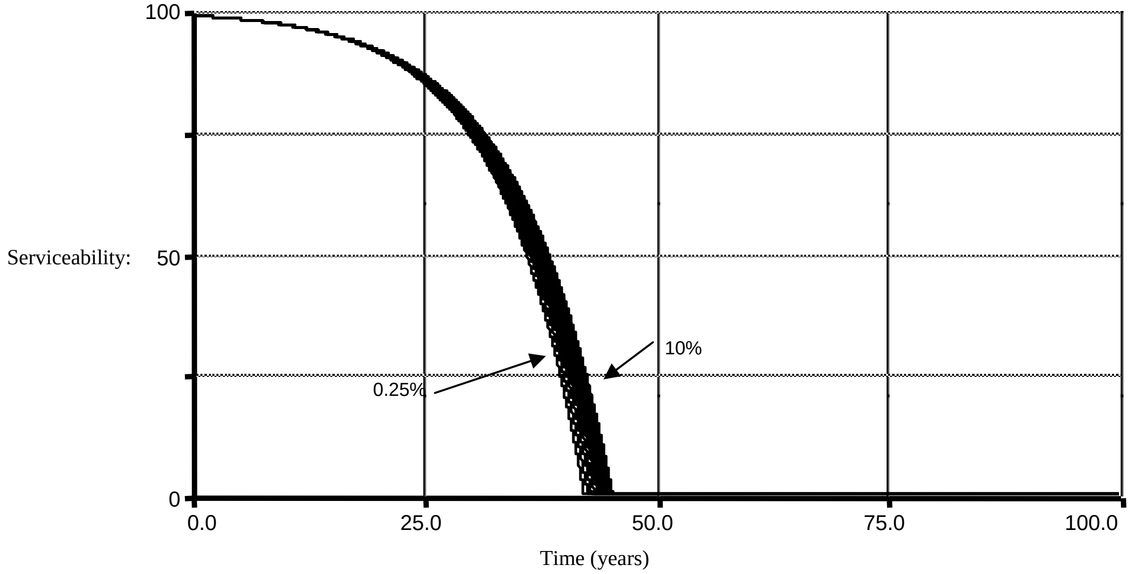

Figure 16 Comparative Serviceability

The next best method is the Condition Assessment method. Looking again at Figure 15, the condition assessment method allows for a more gradual decline in serviceability than the PRV method but still falls short of the PRV method in years of lifespan achieved. The formula method pattern was exactly the same as the no budget method or as if no more maintenance were conducted at all. This leads to the conclusion that the maintenance efforts under this method are so constrained by the budget, that it is of little to no value. It would be better for the users or owner of the facility to fully focus on replacement of the facility on a ten to twelve-year cycle than to continue maintenance in this manner.

The second set of patterns to compare is the total maintenance costs as shown in Figure 17. The first conclusion that can be drawn from the cost comparisons is that 3 of the budget methods produce a linear cost curve the condition assessment method and unlimited budget method. This does not make good sense since degradation growth is not linear.

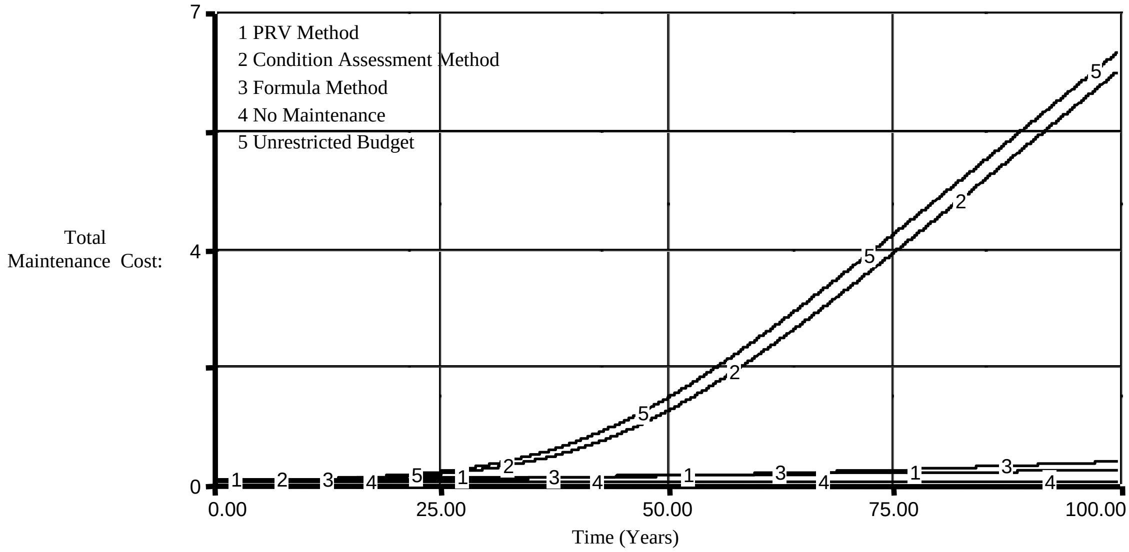

Figure 17 Comparative Maintenance Cost

It would seem that the cost of maintenance would follow degradation growth. The observation that the cost curves do not follow the degradation curves shows serious disconnects in the budget methods from the literature. This is a serious flaw in the methods. The maintenance budget is to preserve serviceability while controlling degradation, but the budget's determination is presently independent of these facility characteristics. In looking at the actual values reported by the maintenance cost outputs, it is important to remember that they are based on the replacement construction costs. Comparison of the cost patterns show that the method with the highest cost is the condition assessment method, followed by the unlimited budget method. The next highest cost is the Air Force's budget method, followed by the lowest cost method which is the formula-based method. While providing serviceability higher than the other methods, the Air Force's PRV method suffers in that it has a disconnect between determination and the actual condition of facility. The final conclusion of the cost comparison is that a link needs to be built between the serviceability of a facility and the determination of its respective budget.

The next set of behaviors for comparison is the maintenance actions, as shown in Figure 18.

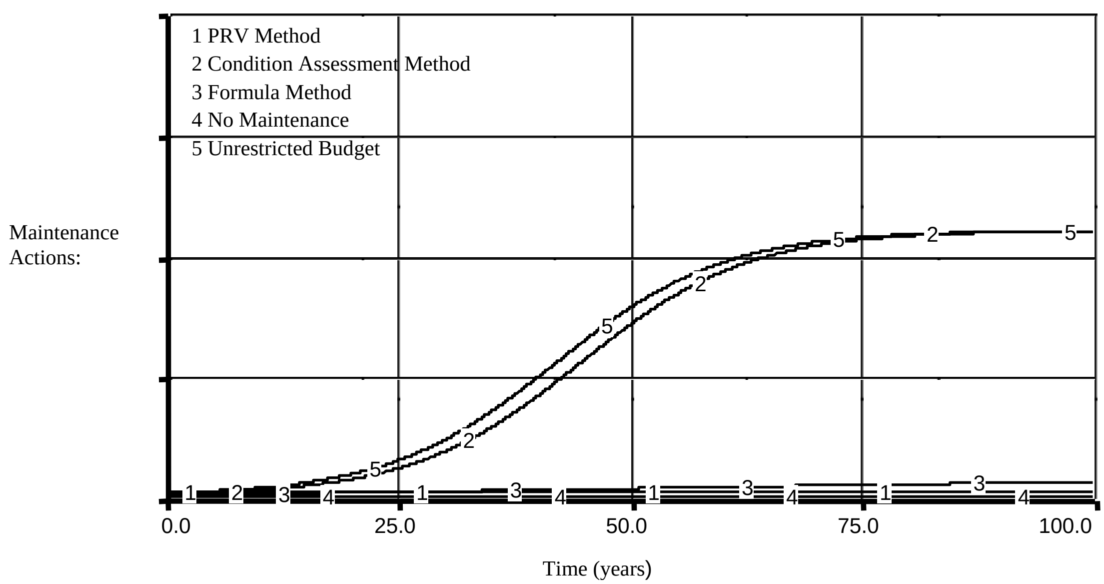

Figure 18 Comparative Maintenance Actions

As with the maintenance costs, the condition assessment method ramps up the number of maintenance actions quickly to a higher level than the other budget methods but does not produce a higher level of serviceability. This leads to the conclusion that degradation growth is only controllable through prevention. The condition assessment method implies that degradation is being repaired after it has taken place. This allows degradation to start growing. Once degradation starts to grow, it is uncontrollable regardless of how much maintenance actions are increased. Therefore, preventative maintenance techniques are extremely important. Another parallel between maintenance actions and maintenance cost is the fact that the Air Force's PRV method and formula method have a constant level of maintenance, while the condition assessment and unrestricted budget method have a growth pattern similar to degradation. Within the PRV and formula method there is no link between degradation and maintenance actions but rather between the budget and maintenance actions (i.e., maintenance is constrained by the budget). This constraint allows an amount of degradation to continually go unchecked, thereby depleting the overall serviceability of the facility. Therefore, a link needs to be constructed to increase the maintenance actions to address the amount of degradation that is not being addressed.

These conclusions show why it is necessary to use a dynamic evaluation of infrastructure methods and not just a snapshot decision analysis tool. Evaluation tools like case studies, multiple criteria decision making alternative based techniques, and even value focused thinking techniques fall short of providing the long term longitudinal look necessary to evaluate the impact of maintenance on facility and infrastructure serviceability. Degradation and maintenance are not static concepts. They need to be continually evaluated over the life-cycle of the facility or infrastructure. In failing to look at an entire facility life-cycle, the following conclusions are often missed. None of the budgeting methods fully stop degradation. Once the degradation starts, it rapidly begins outpacing maintenance actions. It is economically infeasible to correct the situation by increasing the maintenance budget. The initial performance of a budget method is often misleading, providing results that seem good at first, allowing maintenance to keep up with degradation and provide for good serviceability. Therefore, Daum (2004) was correct there are strikingly different results from system dynamics research than static analysis.

V. Conclusion

Summarizing Chapter IV dynamic evaluation's of the budget determination methods are the following conclusions. First, it was demonstrated that none of the methods stop degradation from occurring. Second, it is was shown that in order to control the growth of degradation, the maintenance budget has to be extremely high and disproportionate to the replacement cost of the facility, thereby making it impractical for facility owners and maintainers to consider. The third conclusion was that the entire set of test subject budgetary methods fall short of reaching the desired designed lifespan. The alarming part of this conclusion is that in the initial phase of the facility's life, the budget methods perform equally and appear to be performing at a level that will allow the facility to meet the desired serviceable life. Furthermore, detailed examination of the Air Force PRV method shows that it can be increased six-fold and still not maintain the minimum acceptable serviceability for the facility's entire life span. Fourth it was concluded that maintenance efforts constrained by the budget are of little to no value at all. The fifth conclusion is that the budget methods produce a linear cost curve except the unlimited budget method and condition assessment method. The last conclusion is that degradation growth is only controllable through prevention. These conclusions about the budget determination methods would not have been found in a static decision analysis tool and show why it is necessary to use a dynamic evaluation of infrastructure methods.

After completing this research effort to investigate the methods for maintenance repair budgets and develop a facility or infrastructure maintenance dynamic evaluation model, the research revealed that there are three major areas requiring further investigation. The first area is degradation modeling. The second is using life-cycle cost analysis as a basis for determining facility and infrastructure maintenance cost. The third is the apparent disconnect in facility and infrastructure evaluation criteria as it looks at financial value rather than serviceability. Further evaluation of these three areas will enable a facility-specific dynamic method to be developed that substantially improves the serviceability of Air Force facilities and infrastructure, thereby giving a more accurate picture of the cost of incomplete preventative maintenance.

Further expanding the first area for further study is the modeling of facility and infrastructure degradation. There are tremendous opportunities within this area for dramatic improvement. Predictive techniques for modeling the behavior of facility degradation seem to have been overlooked or ignored by researchers for other efforts into constructive materials, maintenance techniques, and maintenance budget strategies. Understanding how various facility and infrastructure materials degrade is critical to understanding how to develop a budget strategy to maintain facilities or infrastructure items. Degradation cannot be assumed to be too complex to model--it must be explored. Current degradation predictive strategies have focused more on the financial concerns of the facility and infrastructure owners rather than on the serviceability to meet the mission. These methods place too heavy an influence on the value of the facility rather than on the serviceability of the facility or infrastructure. As a result, present methods show depreciation, which is typically heavily front-loaded, as a financial function. These methods show the facility or infrastructure to drop in value rapidly in the initial phase of its life span rather than the behavior pattern asserted in this research. Therefore, it is necessary for more research to be done to find suitable predictors of facility and infrastructure serviceability and degradation that will allow owners and maintainers to more accurately predict where a facility or infrastructure item is in its lifecycle.

The second area to expand on is more analysis is needed to provide a better understanding of total facility and infrastructure life-cycle cost. Presently, too much emphasis is placed on construction or replacement costs for determining the budget for maintenance and repair activities. These methods capture the complexity and size of the facility or infrastructure but neglect other attributes like use, climate, and degradation that have gone un-repaired or neglected. These factors have an adverse impact on serviceability and can produce conditions that require increased maintenance levels and budgets. By replacing plant value or replacement value in maintenance budgeting with a life-cycle cost base for the percentage methods, a more accurate cost estimate for maintenance and repair can be created. Budgets created under this ideology include the facility's life span and maintenance costs with initial construction values. The end result is a more accurate picture of the total facility or infrastructure costs over the life-cycle of the facility. Then when a percentage is calculated for the annual budget, it will produce a budget that will sustain serviceability in light of degradation growth. This will give owners and maintainers the ability to ensure the facility reaches the predicted life span. Life-cycle cost analysis will provide a linkage between designers and maintainers to create more accuracy in the estimates for budgeters.

The third area to expand on is facility evaluation criteria are presently based on financial value rather than remaining serviceability. This very real disconnect was briefly mentioned earlier in the discussion of degradation modeling. Facilities in the Air Force are replaced based upon programmed estimates of work to be done versus the replacement cost of the facility. If this ratio (i.e., Cost of Work to be Done/Replacement Cost) meets or exceeds 70%, the facility is no longer programmed to undergo renovation via repair but is programmed for replacement. This process is solely focused on financial cost estimates of the work to be completed. The facility's remaining serviceability is not evaluated. It is assumed that the cost of the repair work accurately represents the degradation that has occurred to precipitate the repairs, but does it truly mean the serviceability has dropped below the minimum acceptable level presented by Lemer? This evaluation is not taking place. An in-depth evaluation needs to be done to see if maintenance actions, or the lack thereof, precipitated the need for the programmed repair work. More research needs to be done to more closely insert remaining serviceability of the facility into the repair/replacement decision. It further needs to be explored to examine maintenance actions to ensure they are having the desired impact on slowing the degradation growth. The bottom line is that more research needs to be done into which measure is best to use when determining the value of a facility or infrastructure item.

This research effort has been valuable in two major areas. First, it has proven the value and need for dynamic evaluation of maintenance and repair methods. Second, it has served to bring to light areas that need to be further explored. As the three areas of degradation modeling, lifecycle cost analysis, and the disconnect between facility and infrastructure financial value and serviceability are explored, more areas will be unearthed that advance the knowledge base of facility maintenance. These advances will serve to better preserve the serviceability of facilities and infrastructure items and keep them meeting mission requirements into the future.

Appendix A: Model Content

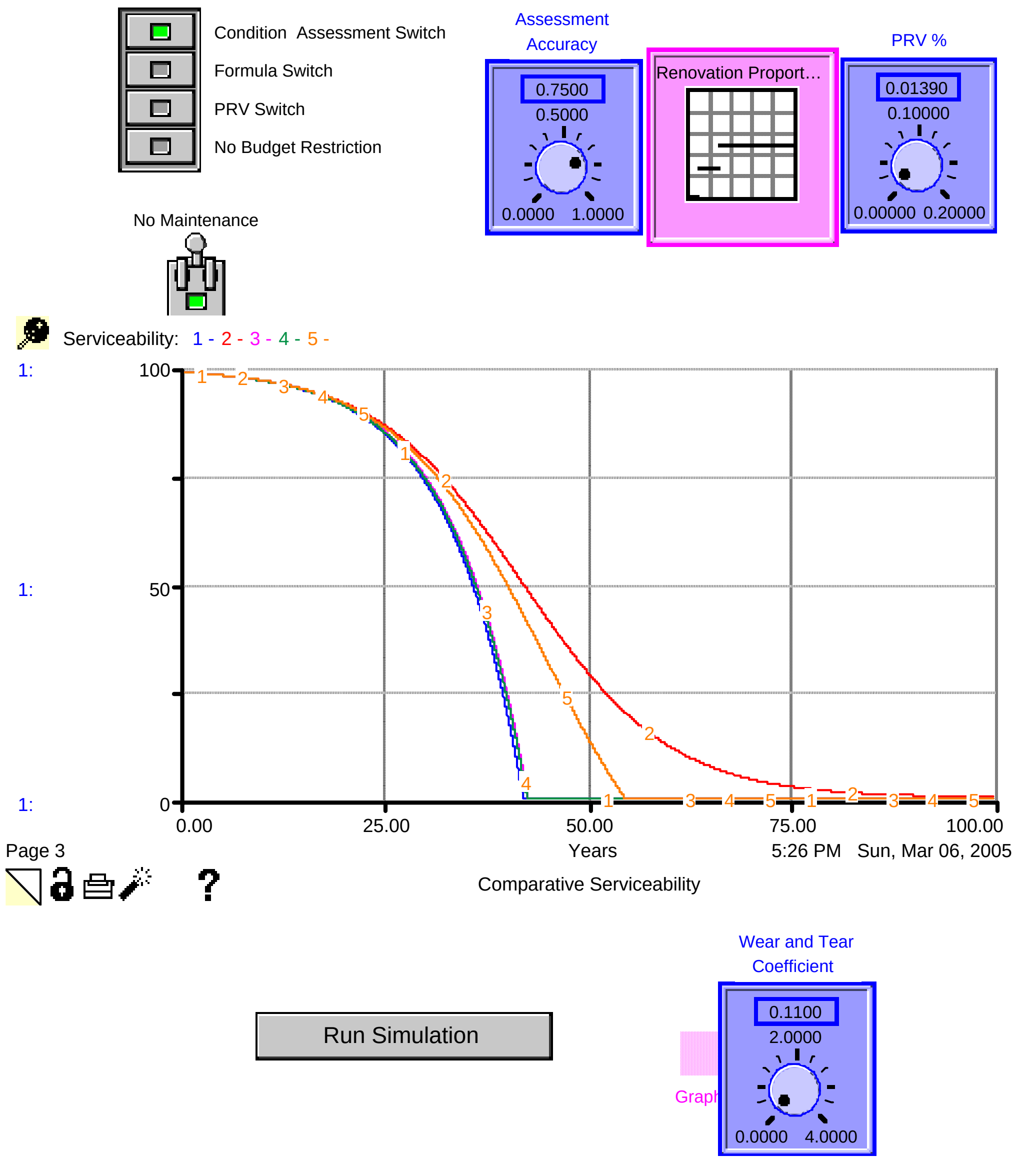

Figure 19 STELLA User Interface

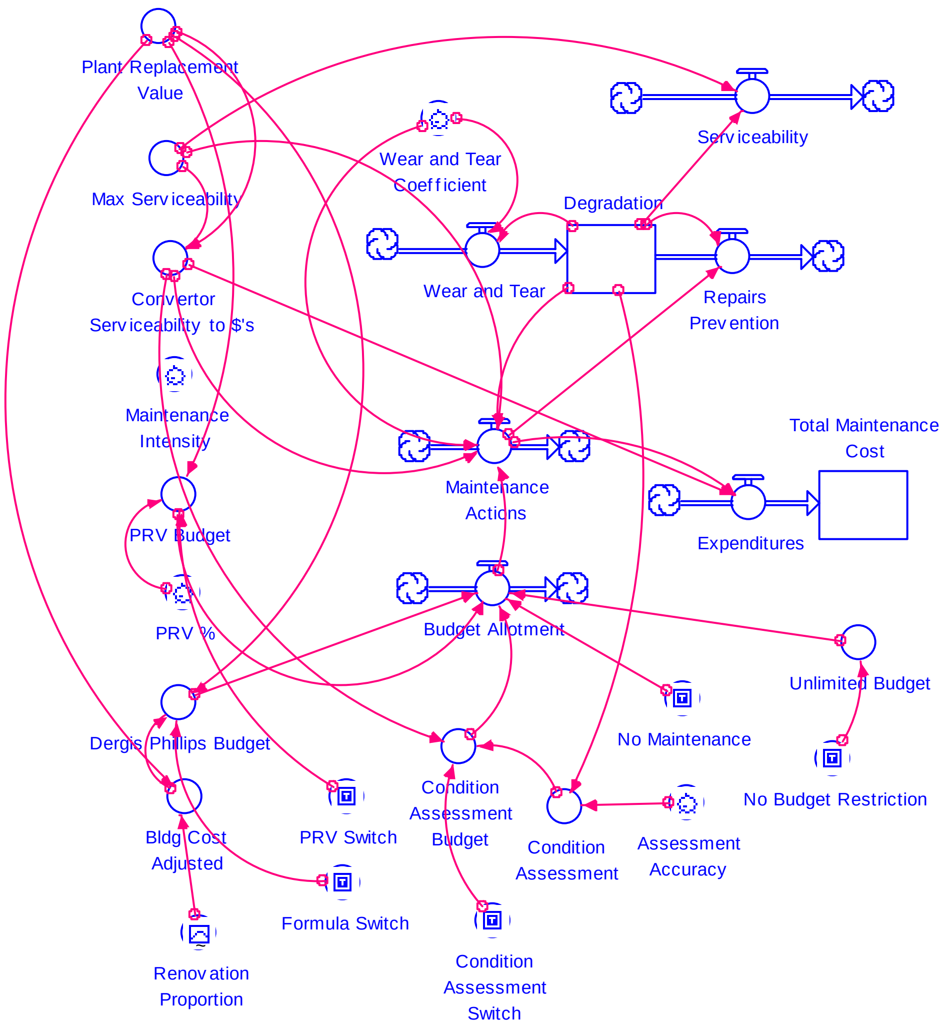

Figure 20 STELLA Flow Diagram

Model Formulations

Degradation(t) = Degradation(t - dt) + (Wear_and_Tear - Repairs__Prevention) * dt
INIT Degradation = 1

INFLOWS:
Wear_and_Tear = Wear_and_Tear__Coefficient*(Degradation)
OUTFLOWS:
Repairs__Prevention = Degradation*Maintenance_Actions
Total_Maintenance__Cost(t) = Total_Maintenance__Cost(t - dt) + (Expenditures) * dt
INIT Total_Maintenance__Cost = Expenditures

INFLOWS:
Expenditures = Maintenance_Actions*Convertor_Serviceability_to_$'s
UNATTACHED:
Budget_Allotment =
(Dergis_Phillips_Budget+PRV_Budget+Condition_Assessment__Budget+Unlimited_Budget)*No_Maintenance
UNATTACHED:
Maintenance_Actions =
(IF(Degradation*Wear_and_Tear__Coefficient/Max_Serviceability>(Wear_and_Tear__Coefficient*Budget_Allotment/Convertor_Serviceability_to_$'s)/Max_Serviceability)THEN((Wear_and_Tear__Coefficient*Budget_Allotment/Convertor_Serviceability_to_$'s)/Max_Serviceability)ELSE(Degradation*Wear_and_Tear__Coefficient/Max_Serviceability))
UNATTACHED:
Serviceability = Max_Serviceability-Degradation
Assessment__Accuracy = .75
Bldg_Cost__Adjusted =
((Renovation_Proportion/Plant_Replacement_Value)*TIME)+(((Plant_Replacement_Value-Renovation_Proportion)/Plant_Replacement_Value)*TIME)
Condition_Assessment__Budget =
Condition__Assessment*Convertor_Serviceability_to_$'s*Condition__Assessment_Switch
Condition__Assessment = Degradation*Assessment__Accuracy
Condition__Assessment_Switch = 1
Convertor_Serviceability_to_$'s = Plant_Replacement_Value/Max_Serviceability
Dergis_Phillips_Budget =
((2/3*(Plant_Replacement_Value))*(Bldg_Cost__Adjusted/1275))*Formula_Switch
Formula_Switch = 1
Maintenance__Intensity = 1.39
Max_Serviceability = 100
No_Budget_Restriction = 1
No_Maintenance = 1
Plant_Replacement_Value = 100
PRV_% = .0139

PRV_Budget = Plant_Replacement_Value*PRV_%*PRV_Switch
PRV_Switch = 1
Unlimited_Budget = 10000000*No_Budget_Restriction
Wear_and_Tear__Coefficient = .11
Renovation_Proportion = GRAPH(TIME)
(0.00, 0.00), (10.0, 30.0), (20.0, 30.0), (30.0, 50.0), (40.0, 50.0), (50.0, 50.0), (60.0, 50.0), (70.0, 50.0), (80.0, 50.0), (90.0, 50.0), (100, 50.0)

Appendix B: Budget Method Test Results

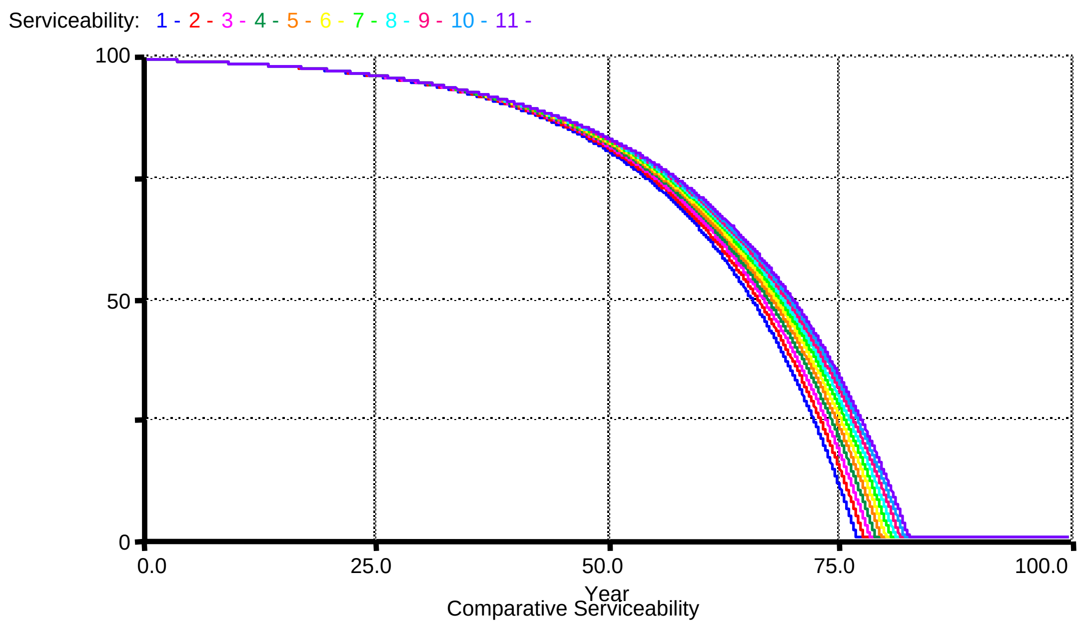

Figure 21 PRV Serviceability at 0.06 Wear and Tear Rate

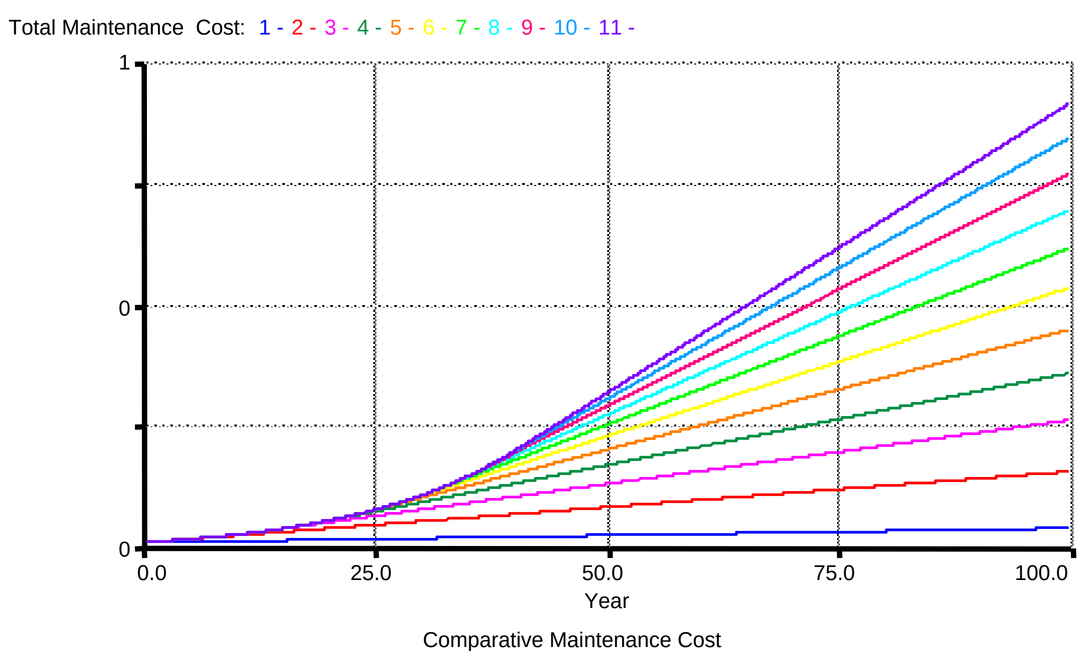

Figure 22 PRV Maintenance Cost at 0.06 Wear and Tear Rate

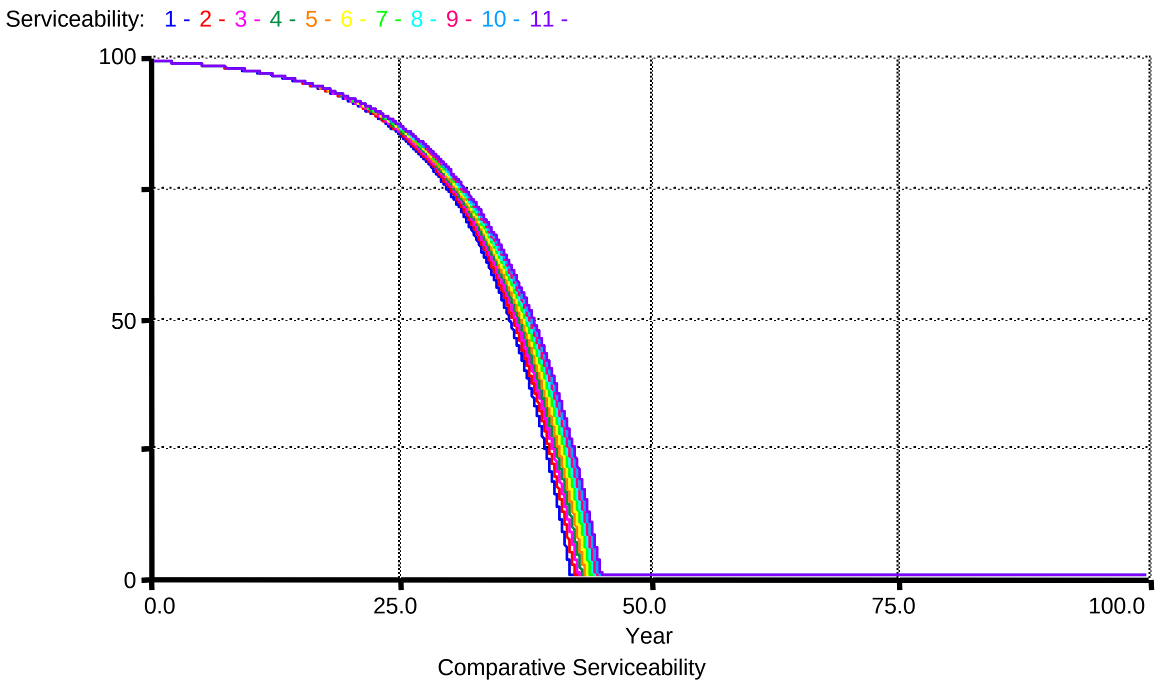

Figure 23 PRV Serviceability at 0.11 Wear and Tear Rate

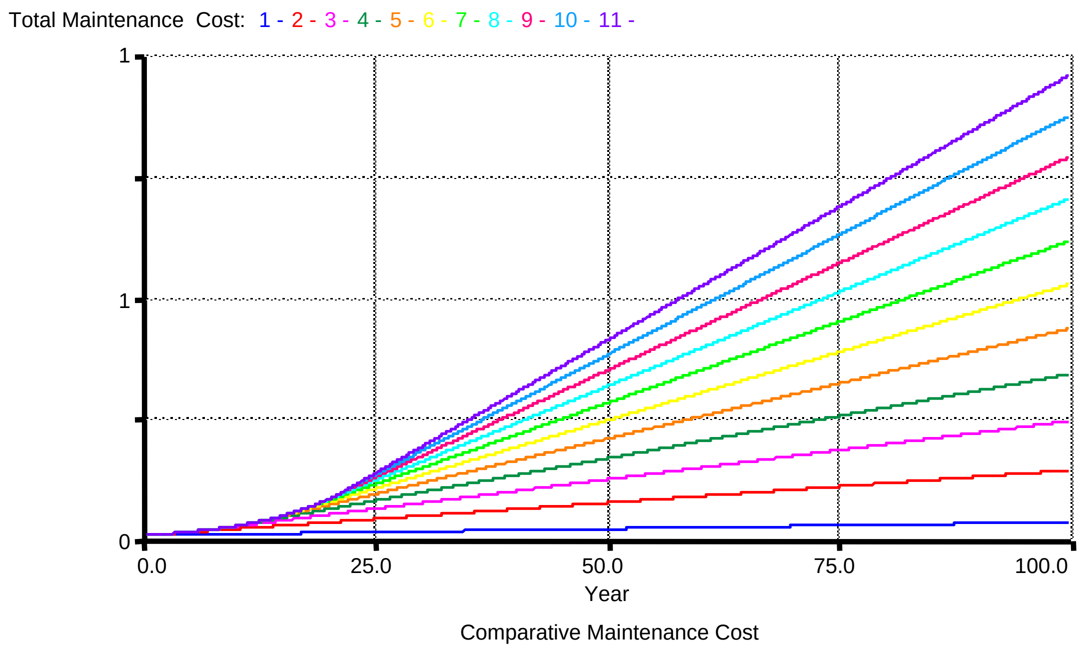

Figure 24 PRV Maintenance Cost at 0.11 Wear and Tear Rate

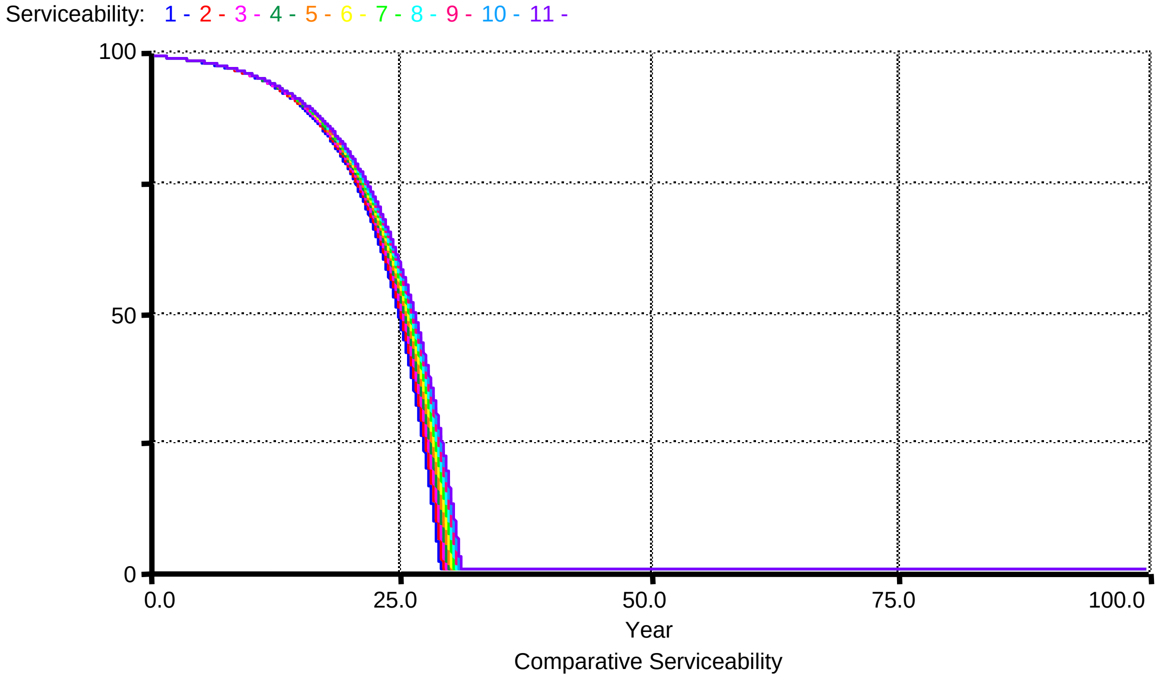

Figure 25 PRV Serviceability at 0.16 Wear and Tear Rate

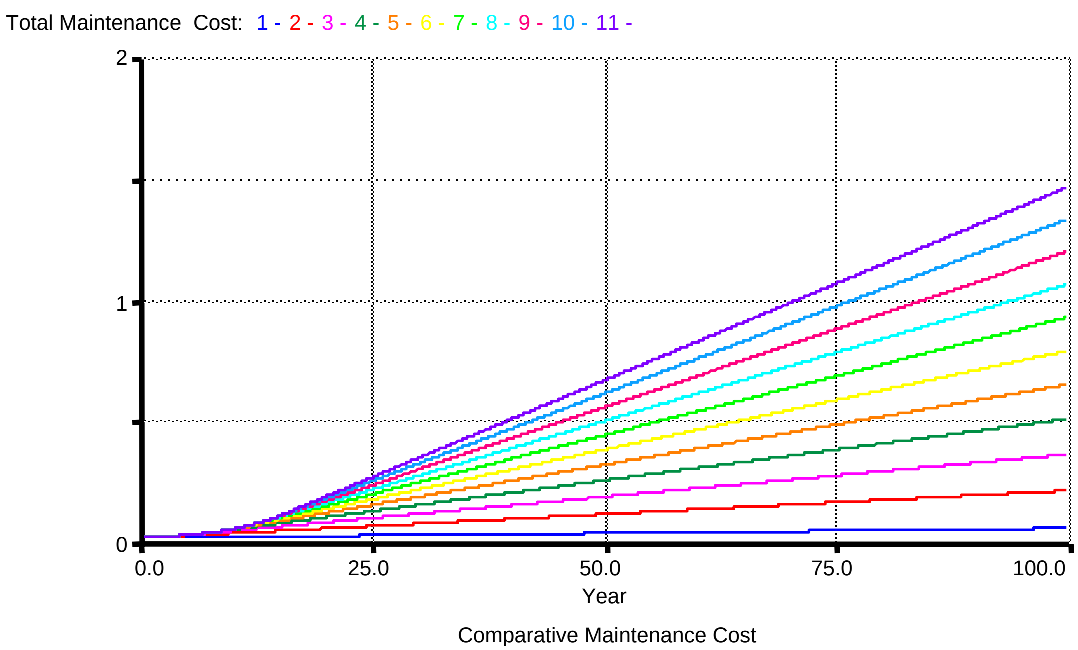

Figure 26 PRV Maintenance Cost at 0.16 Wear and Tear Rate

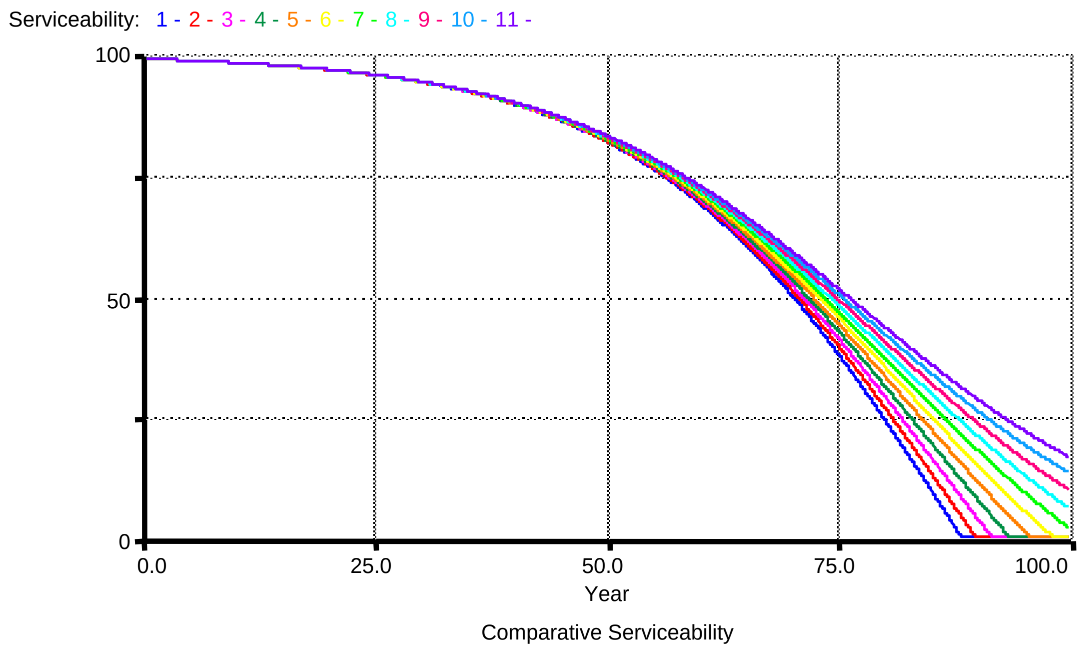

Figure 27 Condition Assessment Serviceability at 0.06 Wear and Tear Rate

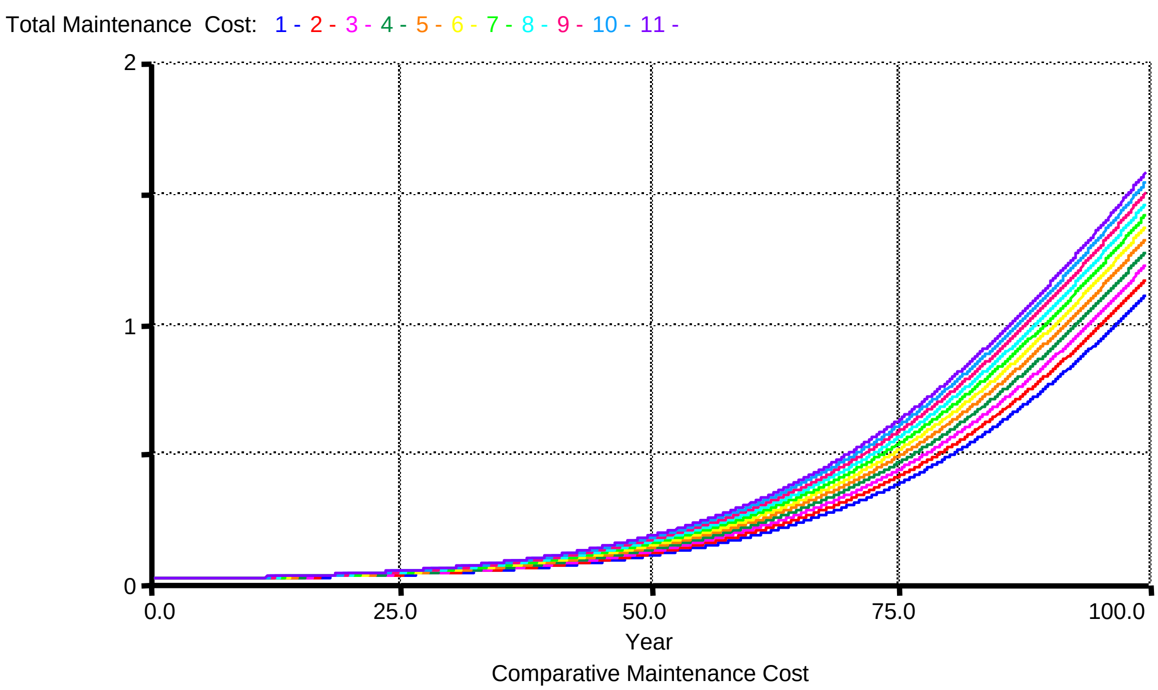

Figure 28 Condition Assessment Maintenance Cost at 0.06 Wear and Tear Rate

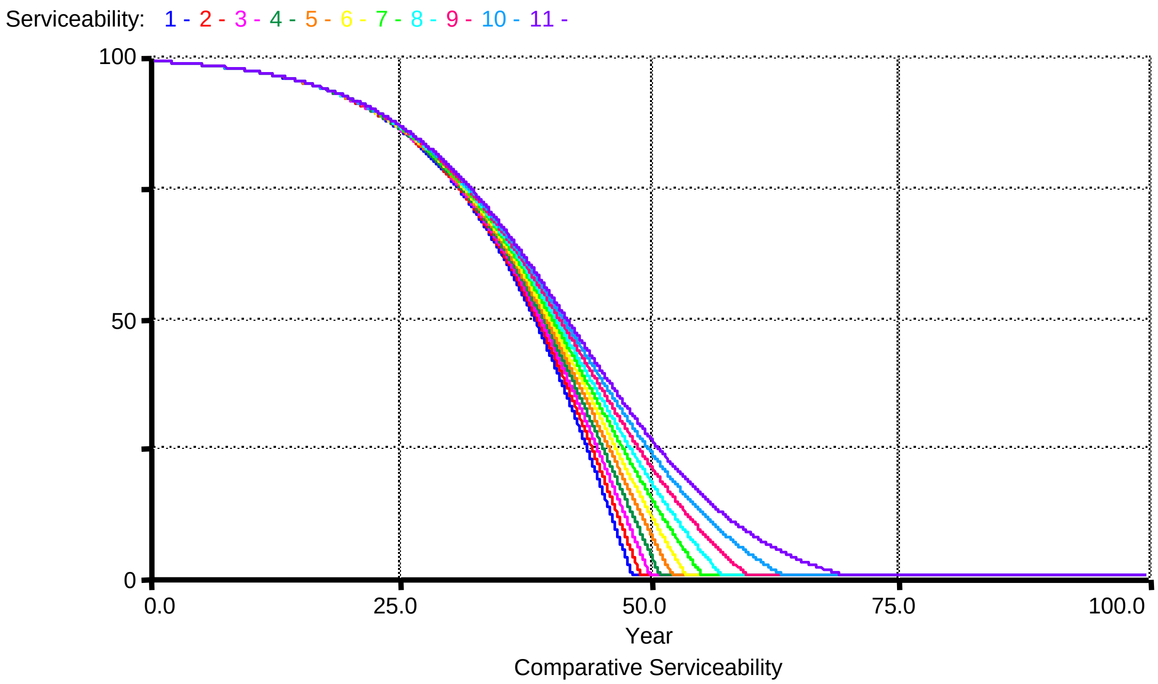

Figure 29 Condition Assessment Serviceability at 0.11 Wear and Tear Rate

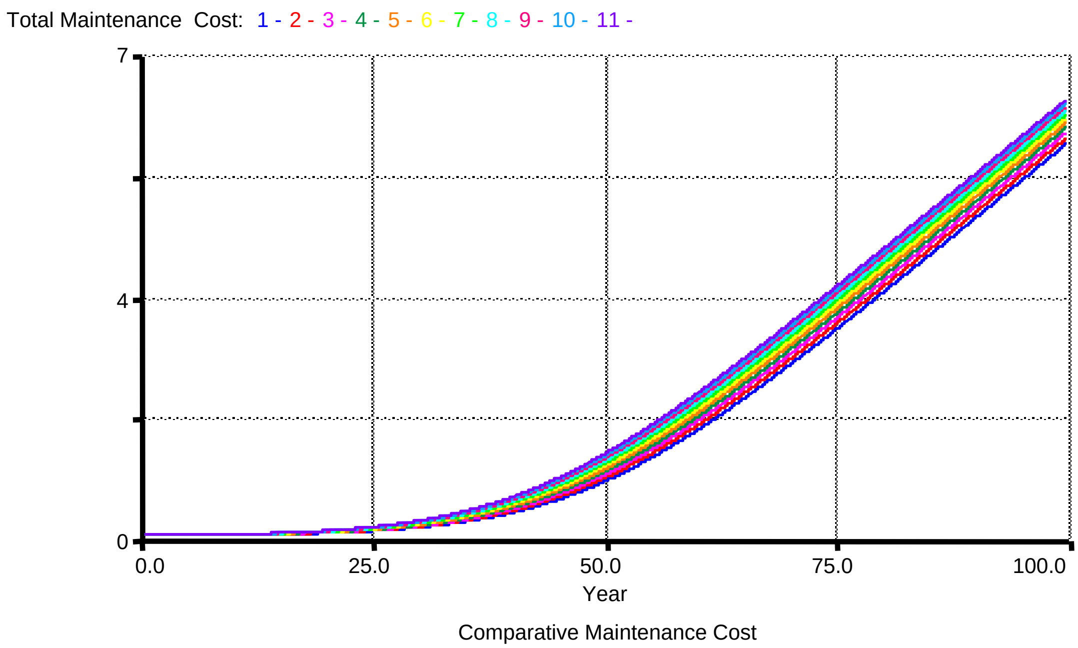

Figure 30 Condition Assessment Maintenance Cost at 0.11 Wear and Tear Rate

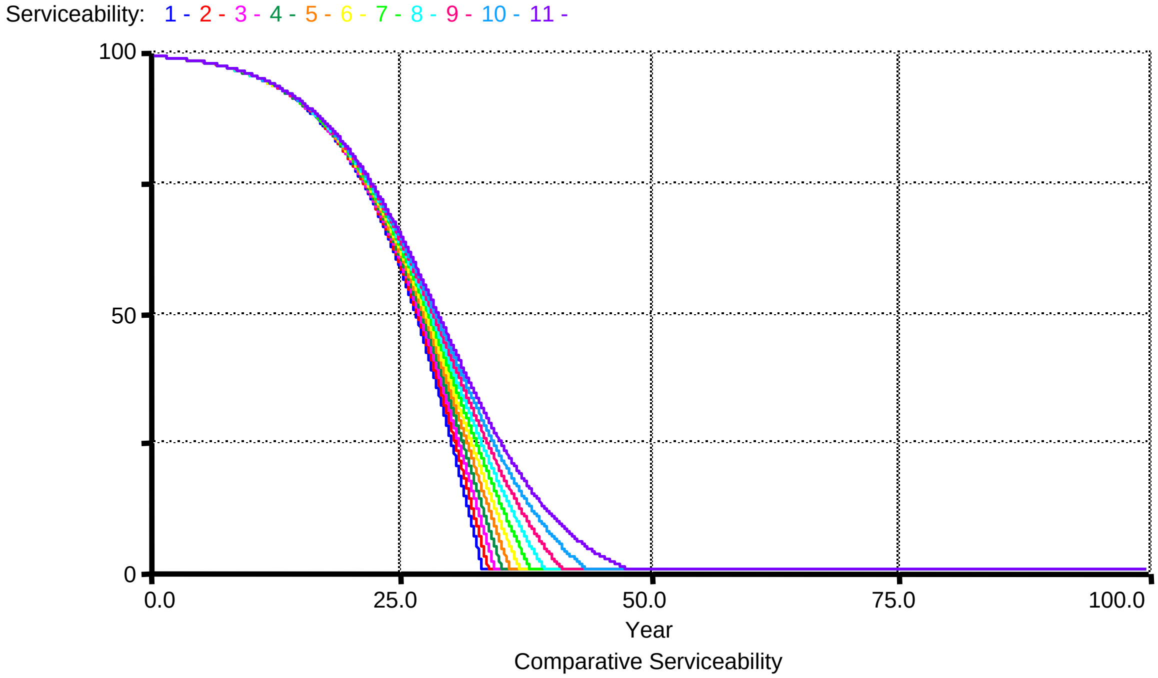

Figure 31 Condition Assessment Serviceability at 0.16 Wear and Tear Rate

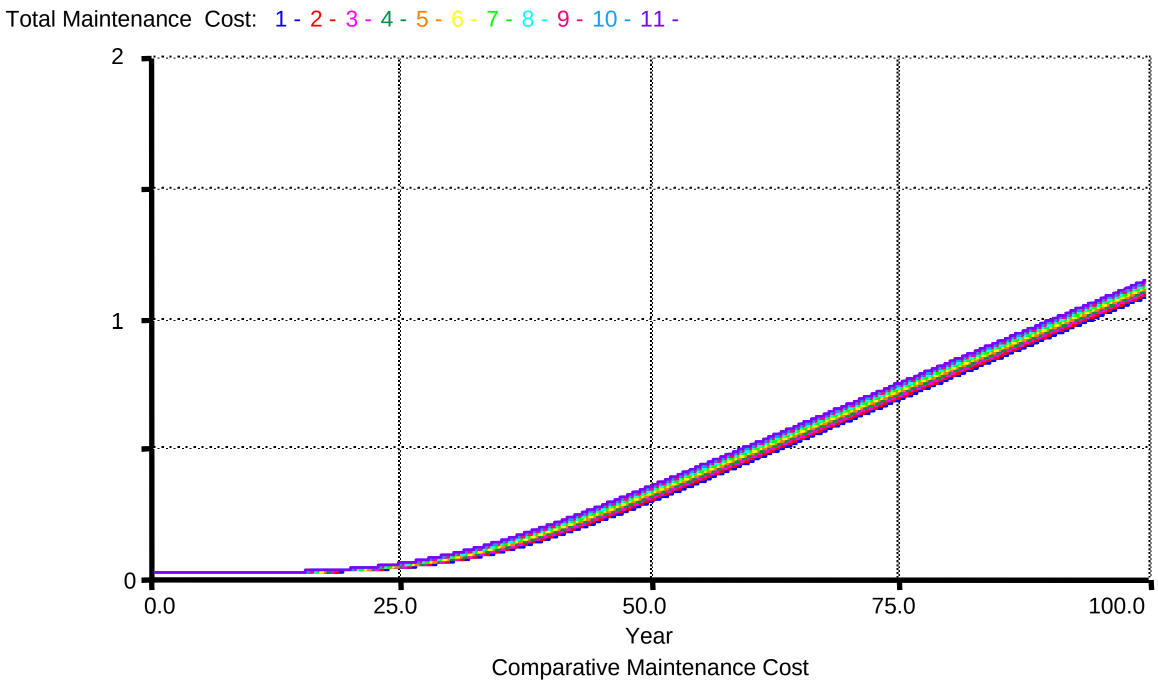

Figure 32 Condition Assessment Maintenance Cost at 0.16 Wear and Tear Rate

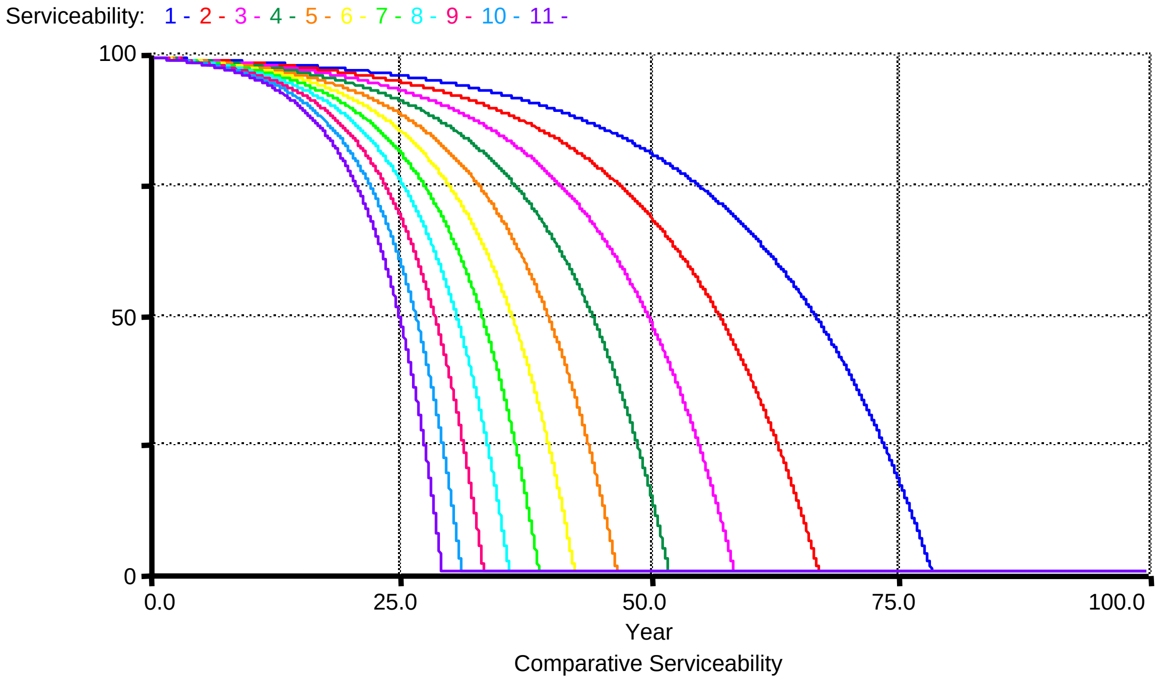

Figure 33 Formula Method Serviceability at varying levels of Wear and Tear Rate

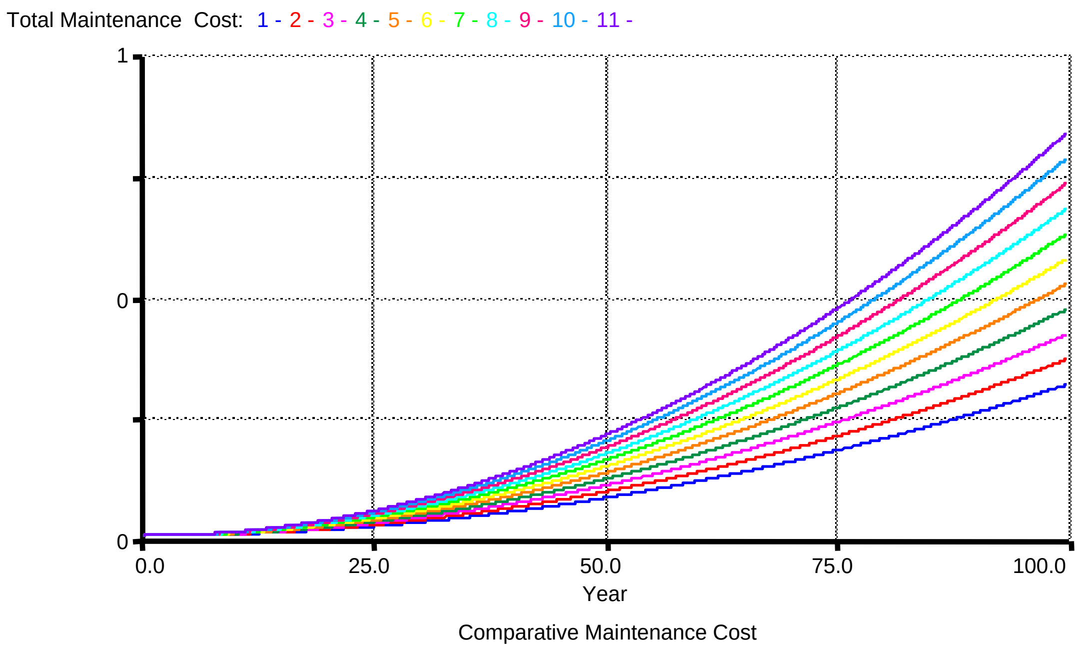

Figure 34 Formula Method Maintenance Cost at varying levels of Wear and Tear Rate

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14. ABSTRACT

The focus of this research is using system dynamics modeling to evaluate the impact of missed scheduled maintenance due to budgetary constraints. Missed maintenance cannot be made up and the benefit to the facility's serviceability is lost. The cumulative effect on an entire facility's life span is that it is unable to reach its designed life expectancy. Replacement construction costs are hundreds, thousands, or millions times more than the annual maintenance repair costs. Therefore, Air Force civil engineers must be capable of evaluating maintenance strategies in a dynamic environment to determine the budget strategy's prolonged effect on infrastructure serviceable life. The results of the evaluation demonstrate how five major categories of infrastructure maintenance budgets change infrastructure's serviceable life. The modeling process provides considerable insight into these budget methods that must be considered to determine what is best for the infrastructures serviceable life.

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